PB83-189274

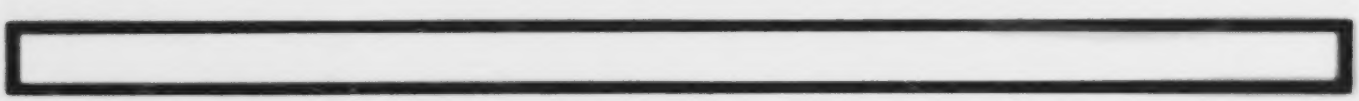
Reducing Runoff Pollution Using Vegetated Borderland for Manure Application Sites

North Carolina State Univ. at Raleigh

Prepared for

Robert S. Kerr Environmental Research Lab.
Ada, OK

Mar 83



U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/2-83-022
March 1983

PB83-139274

REDUCING RUNOFF POLLUTION USING VEGETATED BORDERLAND FOR MANURE APPLICATION SITES

by

Philip W. Westerman
Michael R. Overcash
Samuel C. Bingham
Biological and Agricultural Engineering Department
North Carolina State University
Raleigh, North Carolina 27650

Grant No. R-804608

Project Officer

R. Douglas Kreis
Source Management Branch
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-83-022		PB83 189274

4. TITLE AND SUBTITLE	5. REPORT DATE
Reducing Runoff Pollution Using Vegetated Borderland for Manure Application Sites	March 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
P.W. Westerman, et al.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS School of Agriculture and Life Sciences North Carolina State University Box 5906 Raleigh, NC 27650	10. PROGRAM ELEMENT NO. ABPC 11. CONTRACT/GRANT NO. R-804608
12. SPONSORING AGENCY NAME AND ADDRESS Robert S. Kerr Environmental Research Laboratory U.S. Environmental Protection Agency P.O. Box 1198 Ada, OK 74820	13. TYPE OF REPORT AND PERIOD COVERED Final ( ) 14. SPONSORING AGENCY CODE EPA/600/15

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The objective of this study was to evaluate the mechanisms and effectiveness of vegetated buffer zones or borderland areas in reducing pollutional impact on rainfall runoff from sites used for land application of livestock and poultry manure. The effect of grass buffer-zone length on the reduction of pollutant concentration and mass in runoff from land application areas was studied over a nine-month period for several different buffer-area length/application-area length ratios. Also, one-dimensional mathematical models were developed to investigate the effects of dilution and infiltration.

The model and experimental results suggest that infiltration is the major factor affecting buffer-zone length. Soils having greater infiltration rates will require shorter buffer lengths to obtain the same percent reduction of pollution potential. The results also indicate that required buffer-area length is a function of the application-area length.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Agricultural Wastes Animal Husbandry Waste Disposal	Animal Waste Management Land Application	43F 68D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	97
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

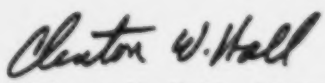
DISCLAIMER

Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency through grant R-804608 to North Carolina State University, it has not been subjected to the Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs to investigate the nature, transport, fate, and management of pollutants in ground water and to develop and demonstrate technologies for treating wastewaters with soils and other natural systems; for controlling pollution from irrigated crop and animal production agricultural activities; for controlling pollution from petroleum refining and petrochemical industries; and for managing pollution resulting from combinations of industrial/industrial and industrial/municipal wastewaters.

This project was initiated to evaluate the mechanisms and effectiveness of vegetated buffer zones or borderland areas in reducing pollutional impact of rainfall runoff from sites used for land application of livestock and poultry manure. The effect of grass buffer-zone length on the reduction of pollutant concentration and mass in runoff from land application areas was for several different buffer-area length/application-area length ratios. One-dimensional mathematical models were developed to investigate the effects of dillution and infiltration. This information is useful in determining optimal practices which will lead to the development of Best Management Practices (BMPs).



Clinton W. Hall, Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

The objective of this study was to evaluate the mechanisms and effectiveness of vegetated buffer zones or borderland areas in reducing pollutional impact of rainfall runoff from sites used for land application of livestock or poultry manure. The effect of grass buffer-zone length on the reduction of pollutant concentration and mass in runoff from land application areas was studied over a nine-month period for several different buffer-area length/application-area length ratios. Also, one-dimensional mathematical models were developed to investigate the effects of dilution and infiltration.

The field study consisted of measuring rainfall runoff pollutional characteristics at various distances downslope from areas where caged-layer poultry manure was applied regularly. Evaluation of nutrients and solids in runoff samples revealed that grass buffer zones effectively reduced the pollutional concentrations, and that the amount of reduction increased with an increase in the ratio of buffer-area length to application-area length.

The model and experimental results suggest that infiltration is the major factor affecting buffer-zone length. Soils having greater infiltration rates will require shorter buffer lengths to obtain the same percent reduction of pollution potential. The results also indicate that required buffer-area length is a function of the application-area length. Application areas having longer slopes require longer buffer lengths to obtain the same percent reduction of the pollution potential. The pollution potential of the application area likewise affects buffer length because a greater percent reduction is required to obtain a desired water quality standard if the application area runoff pollution potential is larger.

This report was submitted in partial fulfillment of Grant No. R-804608 by North Carolina State University under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 5, 1976 to December 31, 1979, and work was completed as of December 31, 1979.

CONTENTS

Foreword.....iii
Abstract..... iv
Figures..... vi
Tables.....viii
Abbreviations and Symbols..... x
Acknowledgment.....xii

1. Introduction..... 1
2. Conclusions..... 3
3. Recommendations..... 5
4. Review of Literature..... 6
5. Infiltration - Dilution Model..... 11
6. Experimental Design and Procedures..... 27
7. Results and Discussion..... 33

References..... 80
Bibliography..... 83

FIGURES

Number		Page
1	Schematic of idealized buffer zone system	12
2	Effect of dilution and infiltration on reduction in concentration through a buffer zone	16
3	Schematic for defining mass reduction through buffer zone	17
4	Effect of infiltration on the reduction of mass through a buffer zone	19
5	Probability of intense 1-hr and 6-hr rainfall to occur in any particular month	25
6	Schematic of application area and buffer zone system during fall and winter	28
7	Schematic of flow collector and distributor	30
8	Amount of TKN on grass as determined from grass sample washings.	38
9	Soil TKN in the surface 2 cm	41
10	Amount of P on grass	42
11	Amount of COD on grass	46
12	Amount of TOC on grass	47
13	Amount of Cl^- on grass	48
14	Effectiveness of the grass buffer zone in removing TKN from rainfall runoff	58
15	Average TKN concentrations for the various buffer-area length/application-area length ratios	60
16	Effectiveness of the grass buffer zone in removing NO_3-N from rainfall runoff	62

FIGURES (Continued)

Number		Page
17	Average NO_3-N concentrations for the various buffer-area length/application-area length ratios	63
18	Effectiveness of the grass buffer zone in removing P from rainfall runoff	64
19	Average P concentrations for the various buffer-area length/application-area length ratios	65
20	Effectiveness of the grass buffer zone in removing COD from rainfall runoff	69
21	Effectiveness of the grass buffer zone in removing TOC from rainfall runoff	70
22	Effectiveness of the grass buffer zone in removing Cl^- from rainfall runoff	71
23	Effectiveness of the grass buffer zone in reducing the VS/TS ratio in rainfall runoff	73
24	Comparison of experimental and model results	77

TABLES

Number		Page
1	Average Percent Reduction of Nutrients (Thompson et al., 1979)	8
2	Research Studies on Overland Flow Treatment of Animal Wastes	9
3	Recommended Overland Flow Filter Areas (Vanderholm et al., 1979)	10
4	Minimum Infiltration Rates for Hydrologic Group (Musgrave, 1955).	21
5	Minimum Infiltration Rates for Soil Textures (Ross et al., 1976).	22
6	Approximate Ranges of Minimum Infiltration Rates for Hydrologic Groups	23
7	Rainfall Frequency Data for Eastern Piedmont Region of North Carolina (Hershfield, 1961)	24
8	Range of D-Factors for Some Possible Design Conditions	26
9	Buffer-Area Length/Application-Area Lengths Ratios	27
10	Characteristics of Poultry Manure	34
11	Amount of Material Applied to the Application Areas	35
12	Amount of Nutrients Applied Versus the Amount of Nutrients Washed from the Grass	36
13	N Analyzed with the Grass and Washed from the Grass	39
14	P Analyzed with the Grass and Washed from the Grass	44
15	Percent Reduction of Pollutants by Filtering of Runoff Samples	49
16	Trends in COD Concentration During Runoff Events	51
17	Trends in TKN Concentration During Runoff Events	52
18	Trends in P Concentration During Runoff Events	52

TABLES (Continued)

Number		Page
19	Trends in NO_3-N Concentration During Runoff Events.....	53
20	Trends in Cl^- Concentration During Runoff Events.....	53
21	Washing of Sampling System.....	54
22	Rainfall During the Experimental Period.....	55
23	Concentration Increases In Runoff Due to Manure Application....	56
24	Average Concentration of Runoff Pollutants.....	57
25	NH_3-N/TKN Ratio Versus Buffer-Area Length/Application-Area Length Ratio.....	59
26	O-PO_4-P/P Ratios for Four Rainfall Events.....	66
27	K_{manure} Evaluation Using Manured-Area Runoff, Soil, and Manure.	74
28	K_{manure} Evaluation Using Manured-Area Runoff, Control Runoff and Manure.....	74
29	K_{manure} Evaluation Using Manured-Area Runoff, Soil-Manure, and Manure.....	75
30	Runoff Volumes for Large Rainfall Events.....	76
31	Hypothetical Range of Buffer-Area Length/Application-Area Length Ratios for Hydrology Groups.....	78

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

UNITS

cm	- centimeter
g	- gram
ha	- hectare
hr	- hour
kg	- kilogram
l or ℓ	- liter
m	- meter
mg	- milligram
ml	- milliliter
mm	- millimeter
t	- metric ton (1000 kg)
s	- second
yr	- year

NUTRIENTS OR POLLUTANTS

Cl^-	- chloride
COD	- chemical oxygen demand
FC	- fecal coliforms
FS	- fecal streptococci
K	- potassium
N	- nitrogen, total nitrogen unless otherwise indicated
Na	- sodium
NH_3-N	- ammonia nitrogen (ammonia nitrogen plus ammonium nitrogen)
NO_3-N	- nitrate nitrogen
O-PO_4-P	- orthophosphate phosphorus
P	- phosphorus, total phosphorus unless otherwise indicated
TC	- total coliforms
TKN	- total Kjeldahl nitrogen (ammonia nitrogen plus organic nitrogen)
TOC	- total organic carbon
TS	- total solids
VS	- volatile solids

SOIL CLASSIFICATION

c	- clay
co	- coarse
f	- fine
l	- loam

ABBREVIATION

s	- sand
si	- silt

MODEL SYMBOLS

C_B	- concentration due to rainfall and other background pollutants
C_o	- concentration at beginning of buffer zone (coming from application area)
C_x	- concentration at distance x into the buffer zone
D or D-Factor	- infiltration rate/rainfall rate ratio (I/R)
I	- infiltration rate
i_e	- rainfall excess (rainfall minus infiltration)
K	- buffer-area length/application-area length ratio (x/W)
K_{manure}	- erodability factor for manure
K_{soil}	- erodability factor for soil in universal soil loss equation
M_o	- pollutant mass input from manured area per unit width perpendicular to flow
M_x	- pollutant mass flow per unit width perpendicular to flow at distance x into buffer zone
M_W	- same as M_o
M_W^B	- pollutant mass entering buffer zone due to background per unit width perpendicular to flow
M_x^B	- pollutant mass leaving buffer zone due to background per unit width perpendicular to flow
M_B'	- rate of mass addition in buffer zone
M_I'	- rate of mass loss by infiltration in buffer zone
M_R'	- rate of pollutant mass input from rainfall directly
M_S'	- rate of pollutant mass input from buffer area soil and vegetation
P_c	- percent reduction in concentration through the buffer zone relative to background concentration
P_m	- percent reduction in mass through the buffer zone relative to background conditions
q	- runoff discharge per unit width perpendicular to flow
q_o	- runoff discharge at beginning of buffer zone
q_x	- runoff discharge at distance x into the buffer zone
R	- rainfall rate
t	- time
W	- application-area length
x	- downslope distance from beginning of buffer zone
y	- depth of flow of runoff

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of this project by the U.S. Environmental Protection Agency and the North Carolina Agricultural Research Service. The direction and support of EPA project officers Lynn R. Shulyer, S. C. Yin, Don A. Clark, and R. Douglas Kreis, are especially acknowledged.

The research project could not have been accomplished without the direction and support of Dr. F. J. Hassler, Head of Biological and Agricultural Engineering Department, and Dr. R. E. Cook, Head of Poultry Science Department, nor without the assistance of Henry V. Marshall, Superintendent in Charge of University Research Units and J. Robert Williams, Unit II Research Unit Superintendent. The professional contributions of Dr. J. C. Barker and Dr. F. J. Humenik are also appreciated.

A special thanks is extended to Ron Horton, June Preston, Dottie deBruyne and other field and laboratory workers who participated in this research.

Thelma Utley is thanked for her excellence in typing of the final report.

SECTION 1

INTRODUCTION

Land application of animal manure has long been recognized as an efficient means of waste disposal and as a means of manure utilization for crop nutrients and soil amendment. In recent years land application of municipal and industrial wastes has increased. Although the experimental part of this study evaluates runoff pollution from land application sites receiving animal manure, many of the principles discussed apply to land application sites receiving other wastes, especially wastes which have high runoff pollution potential for nutrients or oxygen demand. Such wastes are municipal sludge, poultry processing wastes, fermentation sludges, and meat processing wastes.

Land application sites are a potential source of nonpoint source water pollution. Section 208 of the Federal Water Pollution Control Act Amendments of 1972, Public Law No. 92-500, specifies the development of water quality management plans to control nonpoint source pollution. The Environmental Protection Agency proposes the use of Best Management Practices (BMPs). These are defined for agriculture as management practices which best reduce nonpoint source pollution while being consistent with sound agricultural principles. Such BMPs are to be used, in lieu of runoff collection and treatment prior to stream discharge, as the only feasible nonpoint source control measures.

Grass buffer zones are one of the possible BMPs. Other terms used almost interchangeably with grass buffer zone are filter strip, grass filtration area, field borders, or borderland areas. Land application sites near streams, ditches, waterways, or water impoundments can particularly benefit from buffer zones which reduce runoff pollution potential. Mechanisms acting in the buffer area to reduce pollution potential include dilution due to rainfall, infiltration, and settling or filtering of materials. These mechanisms in turn depend upon the vegetation, soil surface condition, soil hydrologic properties, topography and rainfall-runoff conditions. However, very little research has been conducted to determine the size of buffer zone needed for a specified reduction in runoff pollution potential.

The total amount of land required for a complete land application system increases as the buffer-area size increases. Buffer zone research is essential since regulations establishing arbitrary buffer distance can have a tremendous impact on land-based waste treatment system costs.

The objectives of this research were: (1) to develop models based on hydraulic processes to predict reductions of the pollution potential for a land application/buffer zone system and (2) to experimentally determine effectiveness of various buffer lengths based on reduction of runoff pollution concentrations while maintaining a relatively constant manure load on the land application areas.

SECTION 2

CONCLUSIONS

Land application of manure to a grass area by surface spreading increased the pollution transported by rainfall runoff considerably when compared to a similar area not receiving manure. Moreover, a high pollution potential was maintained by frequent manure applications (normally every two to three weeks), and this allowed evaluation of buffer areas under maximum pollution potential conditions.

Grass buffer areas effectively reduced pollutional concentrations of nutrients (such as total phosphorus (P)) and total organic material (total organic carbon (TOC)), and solids in runoff from manured areas. However, to reduce concentrations to within 10% of the concentrations in runoff from a similar area not receiving manure may require a buffer area as large as the manure-application area for soils with low infiltration capacity. The pollutant concentration reduction per unit length of buffer zone was greatest for shortest buffer lengths. Thus, a cost-benefit analysis of buffer zones should consider that as the buffer zone increases there is less improvement in water quality per unit length increase in buffer zone.

One-dimensional overland flow models which were developed were useful in predicting reductions of concentration and mass in a buffer zone. The models are simple in nature, and the results can be generalized in a family of curves. The theoretical model for predicting reduction in pollution concentration is simple because it considers only dilution and infiltration as the pollution-reduction mechanisms. The pollutant mass reduction model considers loss of chemical constituents due only to infiltration of runoff liquid. In both cases, complete mixing of pollutants in overland flow of surface water and infiltrating water is assumed and the results indicate that these assumptions are reasonable.

The models can be generalized by plotting percent reduction of pollution potential (above background conditions) versus the ratio of buffer-area length to application-area length. This can be done for concentration and for mass, resulting in a family of curves for various values of the ratio of rainfall rate to infiltration rate. Thus, the graphs are easy to use if the rainfall and infiltration rates can be quantified for the period of concern. The infiltration rate is dependent on soil types; thus there is some justification for basing buffer length on soil hydrologic groups such as the four groups defined by the Soil Conservation Service (SCS). Soils with higher infiltration rates would require less buffer length.

Experimental results indicated that all pollution parameters which were measured were reduced at similar rates through the buffer zones. Thus, the theoretical model can be applied to all nutrients even though the assumptions used in developing the model seem more appropriate for soluble pollutants than for insoluble pollutants. The theoretical model predicted reductions similar to the experimental results.

The experimental results should not be applied to sites with much longer application area lengths without further research. However, the theoretical model would indicate similar results for larger application areas. Both the experimental results and theoretical model results apply only to when the application area and buffer area are similar in vegetative cover, soil surface condition, topography, and hydrologic properties.

The results of this research provide some guidelines which can be used in determining the amount of buffer area needed to reach a predetermined acceptable level of pollution potential of runoff from land application areas. The results of the dilution-infiltration model can be used in evaluating the cost-effectiveness of changing the buffer-zone length.

SECTION 3

RECOMMENDATIONS

More research should be conducted on the effectiveness of buffer zones in reducing pollution potential of runoff from land application sites of various larger sizes and sites loaded at various rates of manure application. The results of this study indicate that to reduce the concentration of pollutants in runoff from land application sites to near that of similar surrounding areas receiving no manure requires a buffer-zone length about equal to the application-area length. This is more buffer zone than is normally being recommended. If settling, vegetative adsorption or other additional factors besides dilution and infiltration are acting to reduce the pollution in the runoff, then less buffer zone may be needed. Additional research is needed on the mechanisms acting in the buffer zone.

In order to use the dilution-infiltration models on an event-by-event basis, more research is needed on characterizing the effective infiltration rate/rainfall rate ratio, especially for events of highly varying rainfall rates. Also, the capability to predict pollution potential of manure-application sites for different manure types, application rates and soil-vegetation systems needs further development. Effect of relative amounts of manure adhering to leaves and vegetation compared to that which is in contact with soil needs to be evaluated in terms of affecting the runoff pollution potential of the land application site.

Effectiveness of using alternating strips of application areas and buffer areas needs further research. This method may prove to be a more efficient use of land than having one wide buffer area downslope of the manure area because the initial part of the buffer zone seems most effective in reducing pollutants. Also, the effect of type of vegetation in the buffer area needs further research.

SECTION 4

REVIEW OF LITERATURE

INTRODUCTION

The term "buffer zone", when used in reference to sites for land application of manure, usually denotes a strip of land bordering the area which is receiving manure application. This border strip or buffer zone usually does not receive any manure application, and it serves to lessen the impact of the manure application site on the surrounding environment. The buffer zone may include tall vegetation such as shrubs or trees to "hide" the land application area from general public view and to change air movement near the site to reduce odor levels and air transport of aersols which may carry pathogens. These considerations are mainly for air quality and site acceptance by persons in the area. When water quality is considered, buffer zones are utilized to reduce impact of pollution transported from the manure application site by rainfall surface runoff and subsurface water movement.

This study pertains to buffer zones for reducing pollution in rainfall surface runoff from manure application sites. Several mechanisms may be involved in reducing pollution in runoff. Dilution by rainfall in the buffer area is certainly an important factor in reducing concentration. However, to reduce pollutant mass transport requires other mechanisms such as adsorption of pollutants on soil and vegetation, settling, infiltration into the soil, diffusion, and increasing surface detention. Because this reduction of mass is similar to filtering mass from suspension, the terms "filter strip" and "vegetative filters" have become common terms for describing border strips used mainly for controlling runoff pollution impact. In this report the terms "buffer zone" or "buffer area" will be used because the dilution effect can also be important in reducing runoff impact in certain situations. The term "filter" seems to imply that dilution is not included as reducing runoff impact. In addition, "filter" implies a trapping of particulates when actually several other mechanisms are at work in a buffer area to reduce both particulate and soluble pollutant concentrations.

Buffer zones are often recommended to help control the runoff transport of nutrients, sediment, and organic particulates from land areas of high pollution potential and thus lessen the impact of runoff on surface waters. Use of border strips or buffer zones has become a commonly recommended BMP for controlling nonpoint source pollution from agriculture. Soil erosion control practices are also recommended as sound management practices, but their ability to control nutrients is not well established. However, any soil and water conservation practice which reduces erosion and/or increases soil

water retention is a useful management practice to keep soil in place in fields and will likely reduce transport of most nutrients and organic matter. Erosion control practices include shorter slope lengths, strip cropping, contour farming, and terracing. These can be used in combination with buffer zones, and possibly reduce the amount of buffer zone needed to meet runoff quality requirements. More information is needed on effect of traditional erosion control practices on quality and quantity of runoff discharge. Moreover, it is desirable to know the effect of a buffer area for various levels of water quality input, and to know the effect of increasing the buffer area. A few research studies have demonstrated the usefulness of buffer zones in improving water quality of runoff from areas where animal manure has been applied. The results point to a design criteria of having a buffer area nearly equal to application area (depending largely upon the soil hydraulic properties) in order to reduce pollutant concentrations in runoff to levels similar to control areas receiving no manure. These studies have been conducted with highly polluted runoff.

ANIMAL MANURE STUDIES

Areas receiving application of animal manure will often have a higher runoff pollution potential than cropland because application rates of certain nutrients are often higher than normal crop fertilization rates. Also, the manure is often surface applied to grass areas instead of being incorporated in the soil. The availability of pollutants for rainfall runoff is dependent on the manure loading rate, application method, subsequent manure transformations, and on the actual transport mechanisms of particulates and chemical species from a site. These factors have been reviewed by Khaleel et al., (1978) and Reddy et al. (1978, 1979). In general, pollution potential increases with increasing manure loading and decreases with time after manure application. The pollution potential and hydraulic properties of the application area should be determined before designing the buffer zone, because the amount of buffer zone required will depend on the amounts of pollutants entering the buffer zone and the amount of runoff carrying the pollutants. Previous research on buffer strips has not compared buffer strip effectiveness for various loading rates of the manured area.

Two buffer-strip studies (Doyle et al., 1977; Thompson et al., 1979) are similar to this one in that relatively large amounts of animal manure were applied, and the results indicate that when runoff is highly polluted, a buffer strip can result in large reductions in concentration. However, the relationships between pollution potential of the manured area and the amount of buffer area required for different vegetative covers, soil hydrologic properties, topography and rainfall-runoff characteristics have not been well established. Given the small amount of available data, one approach to evaluating the various results is to denote the ratio of buffer area to application area required to reduce concentrations or mass to control or background conditions.

Doyle et al. (1977) evaluated forest buffer strips and grass (Kentucky 31 tall fescue) buffer strips for reducing pollution in runoff from areas receiving dairy manure. The manure application area lengths were 45 m and 5 m for the forest buffer and grass buffer studies, respectively. The forest

buffer area consisted of a mixed population of deciduous trees and uniform ground cover of honey suckle (Lonicera japonica) and had slope of 35-40%. Concentrations of total soluble nitrogen, phosphorus, and potassium (K), and fecal bacteria in surface runoff from the manured area were greatly reduced after 3.8 m of forest buffer, and were further reduced through longer buffer lengths of up to 30.5 m, but the concentrations at distances greater than 3.8 m were not statistically different at the 0.05 level. Rates or volumes of runoff and infiltration were not reported. The manured area for the grass buffer strip study received one application of dairy manure at a rate of 90 t/ha (wet weight) which was a nitrogen (N) application of about 810 kg N/ha. Total mass of pollutants in runoff, but not concentrations, were reported for 5 runoff events occurring within 5 weeks after application. Mass of K, sodium (Na) and nitrate nitrogen (NO_3-N) in runoff from the manured areas compared to runoff from control plots were similar after 4 m of grass buffer strip, but soluble phosphorus mass loading was only reduced about 75% when subtracting out the control and remained twice as great as control. These results are for grass buffer-area length about equal to application-area length and a silt loam soil.

Thompson et al. (1979) applied dairy manure on snow-covered (10-cm deep) areas 24 m in length at a rate of 63 t/ha (about 600 kg N/ha). Pollutant concentration reductions were evaluated in winter runoff for buffer lengths of 12 m and 36 m using three surface conditions: (1) grass surface (orchard grass), (2) corn stubble, and (3) disced corn stubble. Variability of concentrations were large between plots and between years of the two-year study. The overall effectiveness of the three surfaces in reducing pollutant concentration was about equal. Compared to concentrations midway of the 24-m application area, the 2-year average percent reduction of nutrients with background concentrations subtracted out for all plots are shown in Table 1. These results indicate that concentrations of most

TABLE 1. AVERAGE PERCENT REDUCTION OF NUTRIENTS WITH BACKGROUND CONCENTRATIONS SUBTRACTED (Thompson et al., 1979)

Buffer zone length	COD	NH_3	NO_3^-	P	TKN	Average
12 m	78	84	92	68	88	82
36 m	96	109	106	83	93	97

pollutants were reduced between 90 and 100% when subtracting background concentrations with a buffer-area length between 0.5 and 1.5 that of the application-area length. The soil was a moderately well-drained sandy loam with a slope of 4%.

Several other studies have been conducted on overland flow for treatment of animal waste lagoon effluent, and feedlot runoff (Table 2). For these cases, the infiltration area or overland flow treatment area

received highly polluted water input which was not the result of rainfall runoff from an area similar to it in vegetation, soil, and topography. However, the effectiveness of reducing mass and concentration of pollutants in overland flow, with and without rainfall dilution in the treatment area, was demonstrated in these studies.

TABLE 2. RESEARCH STUDIES ON OVERLAND FLOW TREATMENT OF ANIMAL WASTES

Type of animal waste	Treatment system*	References
Beef feedlot runoff	Channelized flow	Edwards et al. (1971) Swanson et al. (1975) Vanderholm et al. (1979)
	Spray-runoff system	Kramer (1974)
	Overland flow	Vanderholm et al. (1979) Young et al. (1978)
Dairy feedlot runoff	Overland flow	Vanderholm et al. (1979)
Swine feedlot runoff	Channelized flow	Sutton et al. (1976) Vanderholm et al. (1979)
Swine anaerobic lagoon effluent	Channelized flow Overland flow	Sievers et al. (1975) Willrich and Boda (1976)
Poultry manure (diluted caged layer manure)	Overland flow	Overcash et al. (1976)

* Some of these systems also included a settling basin, and amount of dilution varied. "Overland flow" is defined as being designed not to have channelization.

Of the studies listed in Table 2, the two most pertinent to this study are those by Overcash et al. (1976) and Vanderholm et al. (1979). Overcash et al. (1976) reported on overland flow treatment of poultry manure. The frequent manure inputs to three terrace systems represented nitrogen loading rates from 1,000 to 2,000 kg N/ha/yr. Mass and concentration reductions were about 70% and 50%, respectively, at 15-m flow length, and about 90% and 65%, respectively, at 30-m flow length. Thus, the initial half of the treatment area was more effective than the last half.

Vanderholm et al. (1979) reported that vegetative filters are an effective means of removing nutrients, solids and oxygen-demanding materials from feedlot runoff. Observed reductions of these constituents by the filter systems under study were over 80% on a concentration basis and over 95% on a mass-balance basis. They also concluded that overland flow is more effective than channelized flow for removal of pollutants. The channelized system requires greater contact time and may have vegetation kill. They proposed

the major nutrient removal mechanisms to be settling, filtration by the vegetation, and adsorption on soil and plant materials. Therefore, they considered flow velocity and contact time to be the major design factors. Contact time is a function of flow distance, flow velocity, slope, and other factors. Infiltration was not included as a design variable for the channelized flow situation but was for the overland flow situation. For channelized flow, the recommended minimum contact time was two hours and recommended contact time increased with increasing feedlot size. For overland flow, the recommended minimum contact time was again two hours, and the flow length was dependent on slope, flow velocity, and infiltration rate. The recommended overland flow area for various soil types are shown in Table 3. Thus, as with the buffer zone studies of Doyle et al. (1977) and Thompson et al. (1979), a filter area or buffer area about equal to feedlot or area receiving manure was recommended.

TABLE 3. RECOMMENDED OVERLAND FLOW FILTER AREAS WITH VARIOUS SOIL TYPES (CLIMATIC CONDITIONS SIMILAR TO THOSE OF CENTRAL ILLINOIS) FROM VANDERHOLM ET AL. (1979)

Soil	Infiltration rate	Minimum filter area
	mm/hr	
Silty clay loam	30.5	1.6 x lot area
Silt loam	38.1	1.0 x lot area
Sandy loam	43.2	0.7 x lot area

One other study listed in Table 2 should be mentioned. Young et al. (1978) investigated the effectiveness of buffer strips for reducing concentration levels in runoff from a beef feedlot under simulated rainfall. They estimated that for 13.7 m of feedlot, a buffer strip of about 33 m of corn or oats would be required to reduce the concentration of nutrients to the same level that might be expected from a field of corn receiving no feedlot runoff. Thus, the recommended buffer area was over twice the feedlot area. A buffer area of orchard grass was about as effective as a corn buffer area. They reported that almost all sediment-associated N and P were removed in the buffer zone. Young et al. (1978) also measured total coliforms (TC) and fecal coliforms (FC) and reported that a buffer strip of at least 35.7 m would be required to reduce the count of TC in runoff from 13.7 m of feedlot to less than 1,000 per 100 ml. Vanderholm et al. (1979) also measured bacteria and reported that bacteria levels in feedlot runoff were not greatly reduced by using the vegetative filter. However, high levels of FC and fecal streptococcus (FS) were found both in the effluent from the filter areas and in the effluent from control areas on which no runoff or manure had been applied. More research is needed on effectiveness of buffer zones in reducing FC and FS.

SECTION 5

INFILTRATION - DILUTION MODEL

INTRODUCTION

Buffer zone effectiveness depends upon a number of factors, some of which are more important than others. Vanderholm et al. (1979) considered the major nutrient removel mechanisms in "vegetative filter strips" to be settling, filtration by the vegetation, and adsorption on soil and plant materials. Their recommendations for filter area design for feedlot runoff are dependent upon contact time (flow velocity and length of filter area), amount of runoff, and the soil infiltration rate in the filter area (enough filter area to infiltrate the lot runoff volume plus the rainfall on the filter area for a certain design storm such as a one year-two hour storm). However, this design approach seems inadequate for storms which result in runoff from the filter area, and most any filter area in humid regions will have runoff during several storms each year. When runoff does occur, a method of predicting pollutant concentrations in runoff is necessary for evaluating pollution potential of the system.

Design considerations for buffer zones adjacent to manure application sites should be similar to filter areas for feedlot runoff except for two main factors: (1) the soil and vegetation characteristics of the manure application area and the buffer zone would usually be similar, whereas they would not for the feedlot and filter area, and (2) the runoff pollutant concentrations for the manure application area would normally be less than for a feedlot. Assuming similar soil, vegetation, and runoff characteristics for the manure application area and the buffer zone area, a hydrologic and pollutant model based on infiltration and dilution can be easily developed with one main assumption needed. That assumption regards how the pollutants are partitioned between the runoff water and the infiltrated water. The pollutants which are filtered or adsorbed on soil or vegetation may not actually infiltrate the soil, but they are lost from the runoff water with the same result as if the pollutants were well-mixed in the rainfall-runoff liquid layer and were infiltrated with rainfall-runoff liquid that enters the soil. This approach was used to develop a runoff model for pollutant concentration and mass transport through a grass buffer zone.

THEORY

Mathematical modeling of one-dimensional overland flow can be used to describe how dilution and infiltration affect concentration and mass of pollutants in runoff when vegetative buffer zones are used with manure

application areas. Consider a buffer zone area situated immediately downslope of a manure application area (Figure 1). The amount of runoff at any point in the waste area and buffer area can be computed using rainfall-runoff theory. Rainfall dilutes the polluted runoff while water and pollutants infiltrate the soil. The concentration of pollutants in runoff at a given distance through a buffer zone can be computed by determining the water and pollutant mass balances.

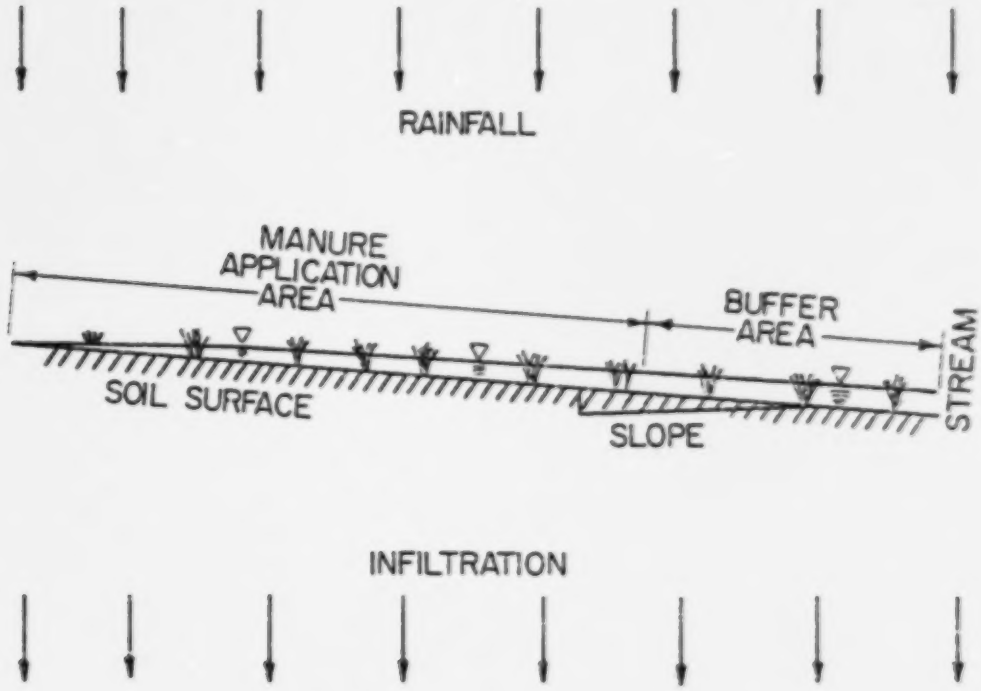


Figure 1. Schematic of idealized buffer zone system.

The hydraulic continuity equation for a unit width perpendicular to downslope surface overland flow can be expressed as:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i_e \qquad (1)$$

where, q = runoff discharge per unit width perpendicular to flow, $\frac{m^3/s}{m}$;

t = time, s;

y = depth of flow, m;

x = downslope distance in buffer zone, m; and

i_e = rainfall excess (i.e. rainfall minus infiltration), $\frac{m^3/s}{m^2}$.

The continuity equation can be simplified by assuming steady-state overland flow (i.e. $\partial y/\partial t = 0$). The assumption is justified when the least infiltration condition is to be modeled because initial unsteady-state infiltration is usually greater, thus increasing buffer zone efficiency. The continuity equation is used in the following form:

$$\frac{\partial q}{\partial x} = i_e \tag{2}$$

Integrating and using the boundary condition $q = q_o$ at $x = 0$, at the top of buffer-zone area, equation (2) can be expressed as:

$$q = q_o + i_e x \tag{3}$$

If steady-state rainfall and infiltration are assumed for the manure application area, then $q_o = W i_e$ where W is the length of the manure application area (in direction of flow) with no runoff entering the manure area from upslope. This would be the case if a diversion is above the manure area or the manure area begins at the top of a hill. Thus, the runoff discharge at any distance is expressed by:

$$q = (W + x) i_e. \tag{4}$$

The purpose of a nutrient or pollutant model is to calculate the reduction in the pollution potential in runoff downslope from a land application site in order to determine the buffer length needed for a particular pollutant discharge. The assumption is made that pollutants move with the water; therefore, the only mass loss of pollutants is by infiltration. However, the concentration is affected by both infiltration and dilution from rainfall. Therefore, equations for determining concentration and mass at any distance x must be determined separately.

Concentration Reduction Model

The mass balance equation downslope through a buffer zone (Figure 1) can be expressed as:

$$M_x = M_o + \int_o^x M_R' \, dx + \int_o^x M_S' \, dx - \int_o^x M_I' \, dx \tag{5}$$

where M_x = pollutant mass flux per unit buffer width perpendicular to flow at distance x into buffer zone, g/s-m;

M_o = pollutant mass input from manure area per unit width perpendicular to flow, g/s-m;

M_R' = rate of pollutant mass input from rainfall directly, g/m^2-s;

M_S' = rate of pollutant mass input from buffer area soil and vegetation, g/m^2-s; and

M_I' = rate of pollutant mass loss by infiltration, g/m^2-s.

Assuming that rate of mass addition in the buffer area is constant and directly proportional to rainfall, then M_R' and M_S' can be lumped together and designated as M_B':

$$M_B' = M_R' + M_S' = RC_B \tag{6}$$

where M_B' = rate of mass addition in buffer zone, g/m^2-s;

R = rainfall rate, m^3/m^2-s; and

C_B = concentration due to rainfall and other background pollutants, g/m^3.

The generation rates M_R' and M_S' are background sources quite separate from the up-gradient presence of manure. These were combined together as equal to the pollutant yield from background conditions, RC_B. The reduction in mass with distance x down the buffer zone is:

$$\frac{d\,M_x}{dx} = RC_B - M_I' \tag{7}$$

The amount of mass infiltrating varies with x. Complete mixing of runoff water and rainfall is assumed so that the pollutant concentration of infiltrating water is equal to that in runoff water, C_x. Therefore, the pollutant mass flux per unit width can be expressed in terms of C_x.

$$M_x = C_x q_x = C_x\,(W+x)(R-I) \tag{8}$$

where C_x = concentration at distance x, g/m^3;

q_x = runoff discharge at distance x, m^3/s-m; and

I = infiltration rate, m^3/m^2-s;

and

$$M_I' = C_x\,I. \tag{9}$$

Assuming infiltration rate, I, and rainfall rate, R, are constant, substituting equations (8) and (9) into equation (7) results in the following linear differential equation:

$$\frac{R}{R-I}\,C_x + W\frac{d\,C_x}{dx} + x\,\frac{d\,C_x}{dx} = \frac{R}{R-I}\,C_B \tag{10}$$

Solving equation (10) and using the boundary condition that $C_x = C_o$ at $x = 0$ results in the equation for C_x:

$$C_x = C_B + (C_o - C_B)\, e^{(\frac{R}{R-I})(\ln \frac{W}{W+x})} \tag{11}$$

Letting $D = \frac{I}{R}$ and $K = \frac{x}{W}$, and simplifying the exponential term, equation (11) becomes:

$$C_x = C_B + (C_o - C_B)\, (\frac{1}{1+K})^{(\frac{1}{1-D})} \tag{12}$$

where D = infiltration rate/rainfall rate ratio; and

K = buffer-area length/application-area length ratio.

The infiltration-to-rainfall ratio would vary in the field and would likely decrease with time. This model does not account for varying D. However, an average D can be calculated from the accumulative infiltration/accumulative rainfall ratio, which is known if total runoff is measured, or a minimum value of D might be considered for design.

The percent reduction in concentration through the buffer zone, P_c, is defined as the reduction relative to background concentration:

$$P_c = (100)\frac{C_o - C_x}{C_o - C_B} \tag{13}$$

Substituting the expression for C_x from equation (12) into equation (13) results in:

$$P_c = 100[1 - (\frac{1}{1+K})^{(\frac{1}{1-D})}] \tag{14}$$

From equation (14), it is evident that the percent reduction above background is not dependent upon C_o or C_B for the assumptions used in the model.

In Figure 2 the results of the concentration reduction model are plotted for a wide range of infiltration rate/rainfall rate ratios (D) and buffer-area length/manure-area length ratios (K). The rate of reduction in concentration decreases with increasing buffer zone distance. When D equals 0, all the reductions are due to dilution.

Development of Mass Reduction Model

The concentration reduction model demonstrates the effect of dilution and infiltration on the reduction of the pollution potential through a buffer area, assuming that pollution potential is reduced when the pollutant concentration of runoff is reduced. While reductions in concentration are important, there are cases when the reduction in mass should also be considered. For example, water impoundments, in which mass settles before

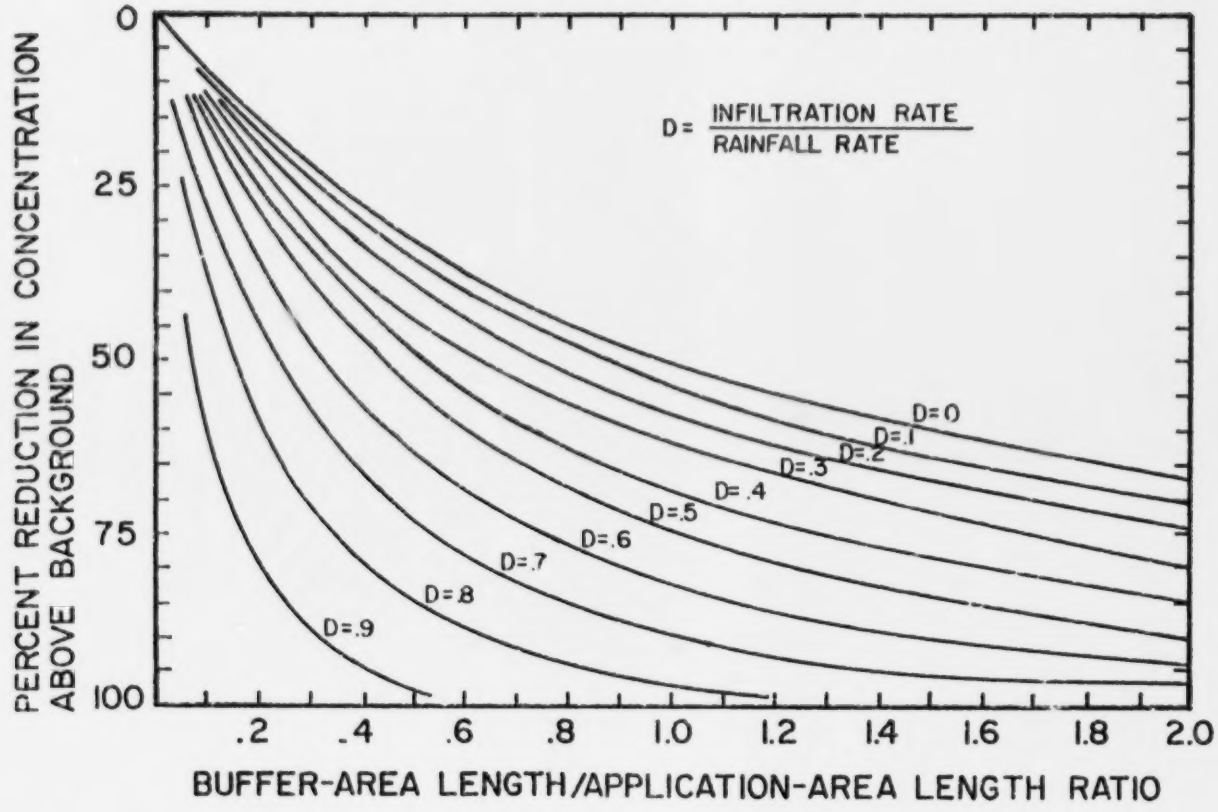


Figure 2. Effect of dilution and infiltration on reduction in concentration through a buffer zone.

the water continues downstream, are adversely affected by mass of pollutants in runoff even though the initial pollutant concentration in the runoff may be relatively low.

Mathematical modeling of one-dimensional overland flow can also be used to predict the reduction in mass through a buffer area due to infiltration. With this approach, rainfall dilution does not affect pollutant mass.

For a visual understanding of percent reduction in mass that exceeds background levels, consider Figure 3. Two areas have identical infiltration characteristics and a stream below. In one of the areas manure is applied at the upper end of the slope above a buffer zone. There is a 100% reduction in pollutant mass through a grass buffer zone from the area having manure application if the mass from both areas (M_x and M_x^B) entering the stream are equal. Because loss of mass is considered to be dependent on infiltration, there would be a zero percent reduction in mass if infiltration is zero.

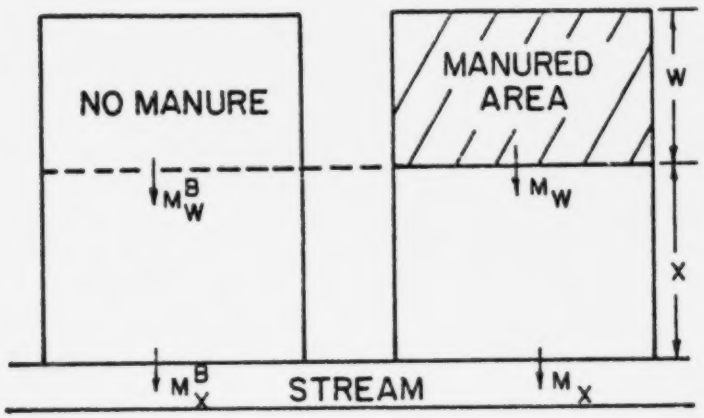


Figure 3. Schematic for defining mass reduction through buffer zone.

Mass at distance x into the buffer zone is defined by equation (8) where C_x is determined from equation (11) or (12). The percent reduction in mass above background conditions, P_m, for a unit width of buffer zone perpendicular to flow is defined as:

$$P_m = \frac{(M_W - M_W^B) - (M_x - M_x^B)}{M_W - M_W^B} (100) \qquad (15)$$

where M_W = total pollutant mass entering buffer zone, per unit width perpendicular to flow, g/s-m;

M_W^B = pollutant mass entering buffer zone due to background per unit width perpendicular to flow, g/s-m;

M_x = total pollutant mass leaving buffer zone per unit width perpendicular to flow, g/s-m; and

M_x^B = pollutant mass leaving buffer zone due to background per unit width perpendicular to flow, g/s-m.

In other words, P_m is the percent reduction in the pollutant mass attributed to the manure area. Expressing the mass as the product of flow volume and pollutant concentration at the end of the zones, the terms in equation (15) are:

$$M_W = W(R-I)C_o \tag{16}$$

$$M_W^B = W(R-I)\ C_B, \tag{17}$$

$$M_X^B = (W + x)(R-I)\ C_B \tag{18}$$

and M_x is defined by equations (8) and (11). After substituting these terms, P_m can be expressed in terms of D and K as:

$$P_m = 100\ [1 - (\frac{1}{1+K})^{(\frac{D}{1-D})}\ ] \tag{19}$$

As with the concentration reduction equation, P_m does not depend on C_o and C_B. However, the absolute values for concentration and mass do depend on C_o and C_B. Thus, achieving an allowable mass discharge into a stream would be dependent on the nature of the manure-application area and conditions of background areas.

The results of the mass reduction model are shown in Figure 4. The percent reduction in mass, P_m, is plotted against the buffer-area length to application-area length ratio, K, for a range of values of the infiltration rate/rainfall rate ratio, D. The percent reduction in mass shows the same general trend as percent reduction in concentration except there are no reductions in mass due to dilution. The total amount of mass would increase through the buffer area if more mass is added in the buffer area from rainfall or from the natural background conditions than is removed by infiltration as runoff passes through buffer areas.

Discussion of Assumptions

Mathematical models are only as good as assumptions placed on them initially. Admittedly, dilution and infiltration are not the only factors decreasing the pollution potential as manure-polluted runoff passes through the buffer zone, but evidence collected so far indicates that these are

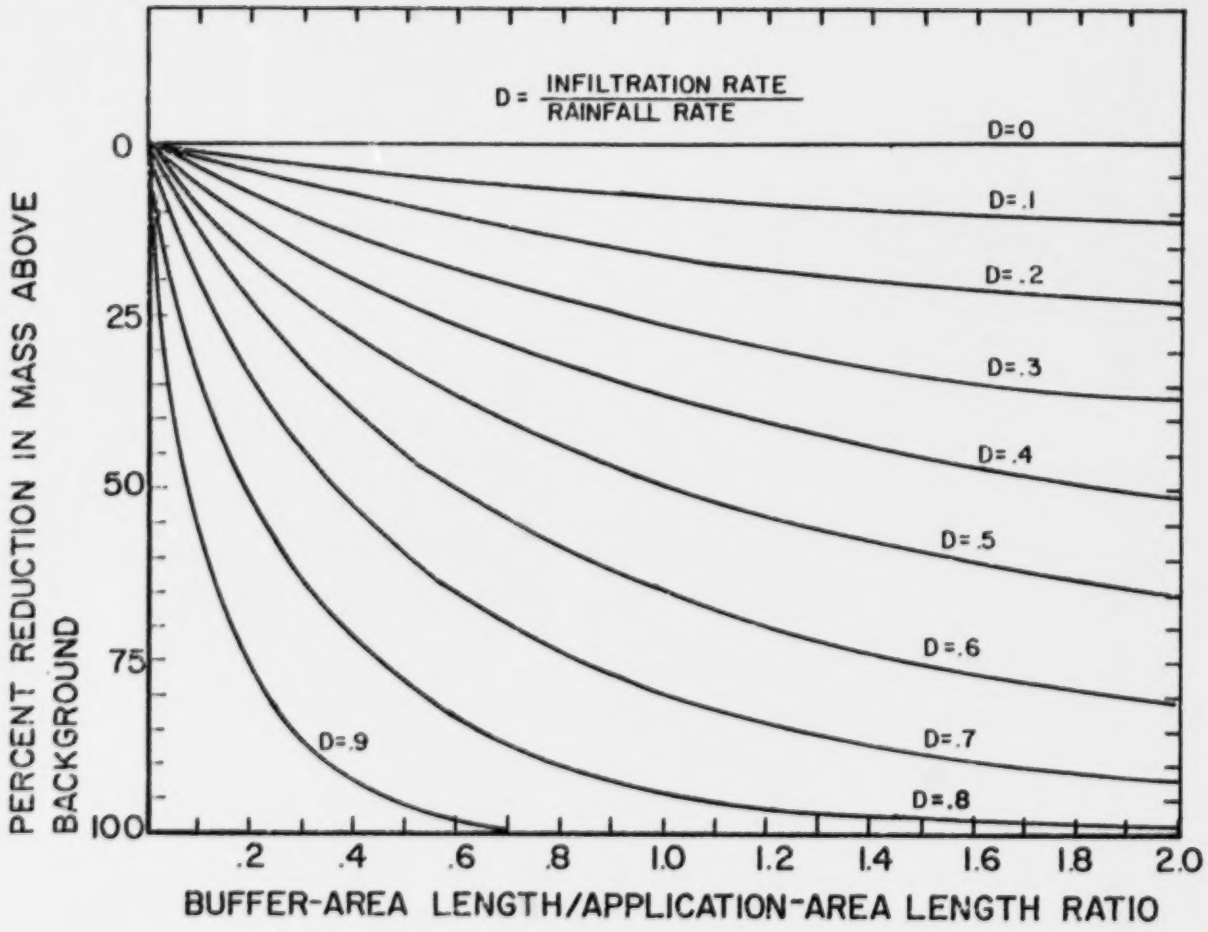


Figure 4. Effect of infiltration on the reduction of mass through a buffer zone.

major factors. A term for removal of pollutant mass by settling and adsorption could be added or substituted for the mass infiltration term. This term would likely vary with different nutrients, and be dependent on the vegetation, the soil, and the amount and characteristics of the suspended solids. The assumption that rainfall and runoff are well mixed and that pollutant concentration of infiltration is equal to that in runoff at a particular location tends to lump all removal mechanisms into this one term. Although this assumption should be best for soluble nutrients such as nitrate, the research data collected thus far indicates that this assumption leads to a reasonable prediction of pollutant reduction of most any pollutant. This result may be partly due to the various removal mechanisms tending to have an exponential decay, or, in other words, the efficiency of pollutant removal mechanisms decreasing as the pollutant concentration decreases. However, letting the mass infiltration depend on runoff and infiltration, as in the assumption of the researchers, makes it easy to combine the hydrologic model with the pollutant transport model and also indirectly take into account some other variables, such as vegetation, which affect runoff and infiltration as well as possibly pollutant settling or adsorption.

The hydrologic assumptions that rainfall and infiltration are uniform and steady-state require that the mean conditions be used or that a critical case of short time interval be chosen. Potential for pollution of runoff is likely greatest during initial runoff, because the amounts of pollutants at the soil surface or on vegetation are greatest then, but infiltration capacity is also normally greatest at the start of the storm and decreases with time. Variable infiltration and pollution potential of the application area would complicate the model, and would probably require numerical techniques and computer solution.

The concentration reduction model predicts the percent reduction in the pollution potential where the pollution potential is the difference between the concentration from a manure-application area and that from a background area. Since the percent reduction in pollution potential does not depend on the magnitude of the pollution potential (i.e. C_O and C_B may be any value), different percent reductions may need to be used in the design of buffer zones depending on the magnitude of the pollution potential. For example, given a D factor of 0.8, reducing a concentration of NO_3-N from 10 mg/l higher than background levels to only 2 mg/l higher (80 percent reduction) would require a 0.4 ratio of buffer-area length to manure-area length. If the original concentration were 20 mg/l higher than background, achieving the same 2 mg/l higher than background result (90 percent reduction) would require a 0.64 ratio.

Determining the magnitude of the pollution potential of a proposed application area presents a problem because so many factors influence the availability of manure constituents for runoff. Although general ranges of values of pollutant concentrations in runoff from land application sites and other land uses could be estimated from the literature (Loehr, 1974; Khaleel et al., 1978; Gilbertson et al., 1980), the values for a particular site would depend upon the site characteristics (soil type, vegetation, topography, etc.), application rates of manure, hydrologic conditions

(especially immediately after surface manure application), method of manure application, and other climatic, physical, biological and chemical factors. Values for background conditions will also vary for different sites. The data requirements for design inputs and verification and the choosing of design safety factors will depend on the sensitivity of the receiving waters to increased pollution. The uncertainity in predicting pollution potential of manured areas and background conditions for a particular site signifies that the design of buffer zones will be approximate, and this should be considered when choosing design methodology, setting water quality criteria, and performing cost-benefit analyses of buffer zones.

EVALUATING THE INFILTRATION-RAINFALL FACTOR

The inputs required for using equations (14) and (15), or Figures 2 and 4, to choose buffer-zone length (as ratio to application-area length) are the pollution potential (above background) due to the manure-application area, the infiltration to rainfall ratio (D-factor), and the desired reduction in concentration or mass through the buffer zone. Although pollution potential and rainfall-infiltration characteristics for a particular site are difficult to predict, considerably more information exists for rainfall and infiltration than for pollution potential. The principal factors to consider when choosing a design D-factor can be evaluated in terms of general ranges of values for infiltration rates and rainfall rates.

Infiltration

The SCS placed soils into four hydrologic groups (A, B, C, and D) on the basis of infiltration rates (SCS, 1964). The groups are based on the premise that similar soils (similar in depth, organic matter content, structure, and degree of swelling when saturated) will respond in a similar manner during a rainstorm. Musgrave (1955) gave estimates of minimum infiltration rates for these SCS hydrologic groups (Table 4). If the impeding strata approaches clay then minimum infiltration is near the lower limit, and if the impeding layer approaches sand then the minimum infiltration is near the upper limit.

TABLE 4. MINIMUM INFILTRATION RATES FOR HYDROLOGIC GROUPS (MUSGRAVE, 1955)*

Hydrologic group	Minimum infiltration (cm/hr)
A	0.75 to 1.15
B	0.40 to 0.75
C	0.15 to 0.40
D	0.00 to 0.15

* Determined on soils having a minimum cover, thoroughly wetted, and after a long rain in excess of the infiltration rate.

The minimum rates are determined on soils having minimum cover, and after a long rain in excess of the infiltration rate. The minimum infiltration rate given by Musgrave (1955) may be too small since a grass buffer zone has a cover; therefore, an infiltration rate based on the saturated hydraulic conductivity may be a better design rate. Mein and Larson (1971), Green and Ampt (1911), and others use the saturated hydraulic conductivity as the limiting (minimum) infiltration rate in their analyses. Li et al. (1976) defined the long-term average hydraulic conductivity in the wetted zone as one-half of the saturated hydraulic conductivity. The average hydraulic conductivity may be a better estimate of the minimum infiltration rate when factors such as soil cover do not limit infiltration. In Table 5, estimates of saturated hydrauilc conductivity for different soil textures taken from Ross et al. (1976), and the minimum infiltration rates are given.

TABLE 5. MINIMUM INFILTRATION RATES FOR SOIL TEXTURES (ROSS ET AL. 1976)*

Hydrologic group	Soil texture#	Saturated hydrauilc conductivity (cm/hr)	Minimum infiltration rate (cm/hr)
A	cosl	38	19
	s	63	32
	ls	57	28
B	sl	12.6	6.2
	si	6.7	3.3
	fsl	7.6	3.8
C	l	2.5	1.25
	sil	2.6	1.3
	scl	2.3	1.1
D	cl	0.88	0.44
	sicl	0.61	0.30
	sc	0.78	0.39
	sic	0.37	0.19
	c	0.46	0.23

*Based on one-half of the saturated hydraulic conductivity.

#co = coarse, f = fine, s = sand, l = loam, c = clay, and si = silt.

Depending on the conditions of the soil-cover complex, an infiltration rate can be selected between the two minima of Tables 4 and 5. If crusting and/or freezing of the soil are a problem, perhaps the lower infiltration rate will be a more realistic rate to use. On the other hand, a soil with adequate vegetation could probably use a higher minimum infiltration design rate. Combining the data by Musgrave (1955), Table 4, and Ross et al. (1976), Table 5, an approximate range of minimum infiltration rates for different hydrologic groups is given in Table 6.

TABLE 6. APPROXIMATE RANGES OF MINIMUM INFILTRATION RATES FOR HYDROLOGIC GROUPS BASED ON DATA FROM MUSGRAVE (1955) AND ROSS ET AL. (1976)

Hydrologic group	Minimum infiltration rates (cm/hr)
A	0.75 - 25
B	0.40 - 5.0
C	0.15 - 1.25
D	0 - 0.25

Rainfall Intensities

Most runoff occurs from high intensity periods of rain or from long periods of moderate rainfall intensity, depending upon the rainfall intensity and infiltration rate capacity. If the soil is frozen or saturated, low intensity rain may produce runoff. Therefore, the design storm to use for designing a buffer zone will likely depend upon what is considered the most critical situation. This would depend not only on the expected rainfall-runoff and infiltration capacity, but also on the manure loading schedule as it affects pollution potential, and stream system sensitivity to increased pollution. For example, if winter runoff was thought to have the worst pollution potential, a winter-type storm would be used for design purposes. For North Carolina, a long-duration moderate-intensity rain event is more probable in winter than a short-duration, high-intensity rain event. Hershfield (1961) gives the probability of an 1-hr and 6-hr rain event of various return periods occurring during months of any particular year (Table 7 and Figure 5). During the winter months (November - March), the probabilities of an intensity as great as the 1-hr storm in Table 7 are negligible, while the probabilities for the 6-hr storm are small but somewhat greater than for the 1-hr storm. Both the 1-hr and 6-hr storms are much more likely to occur in summer. Therefore, the design return period might be 10 years for summer conditions and perhaps one year for winter conditions to make probability of occurrence more the same for two seasons. However, these are refinements in the design, and are dependent on knowledge of rainfall, runoff, and infiltration characteristics for the location, and also on knowledge of water quality effects and on water quality criteria.

Magnitude of D-Factor

Because rainfall intensity and infiltration capacity vary, the D-factor (ratio of infiltration capacity to rainfall intensity) can vary over a wide range. Also, for determining water quality effects the total runoff should be considered along with the rate of runoff. D-factors and total runoff for a clay loam and a sandy loam soil are shown in Table 8 for minimum infiltration rates and maximum rainfall intensities for two possible design storms.

TABLE 7. RAINFALL FREQUENCY DATA FOR EASTERN PIEDMONT REGION OF NORTH CAROLINA (HERSHFIELD, 1961)

Return period (years)	Duration (hours)	Total rain (cm)	Average intensity (cm/hr)
1	1	4.1	4.1
2	1	4.6	4.6
5	1	5.6	5.6
10	1	6.6	6.6
25	1	8.1	8.1
50	1	8.6	8.6
100	1	9.4	9.4
1	6	5.8	1.0
2	6	6.6	1.1
5	6	8.9	1.5
10	6	10.2	1.7
25	6	11.7	2.0
50	6	13.2	2.2
100	6	15.2	2.5

The D-factors in Table 8 represent extreme values since infiltration rates are usually greater than the minimum rate and rainfall intensities are less than the maximum rate. The large differences in D-factors between soil textures suggest that soils (infiltration) are a major factor. For design purposes, the D-factors in Table 8 may prove too conservative. The nutrient model results, in conjunction with experimental data, can be used to determine a more realistic D-factor for a particular hydrologic group. Also, the assumption that pollutant mass loss is directly related to infiltration needs further research, particularly for low infiltration rates.

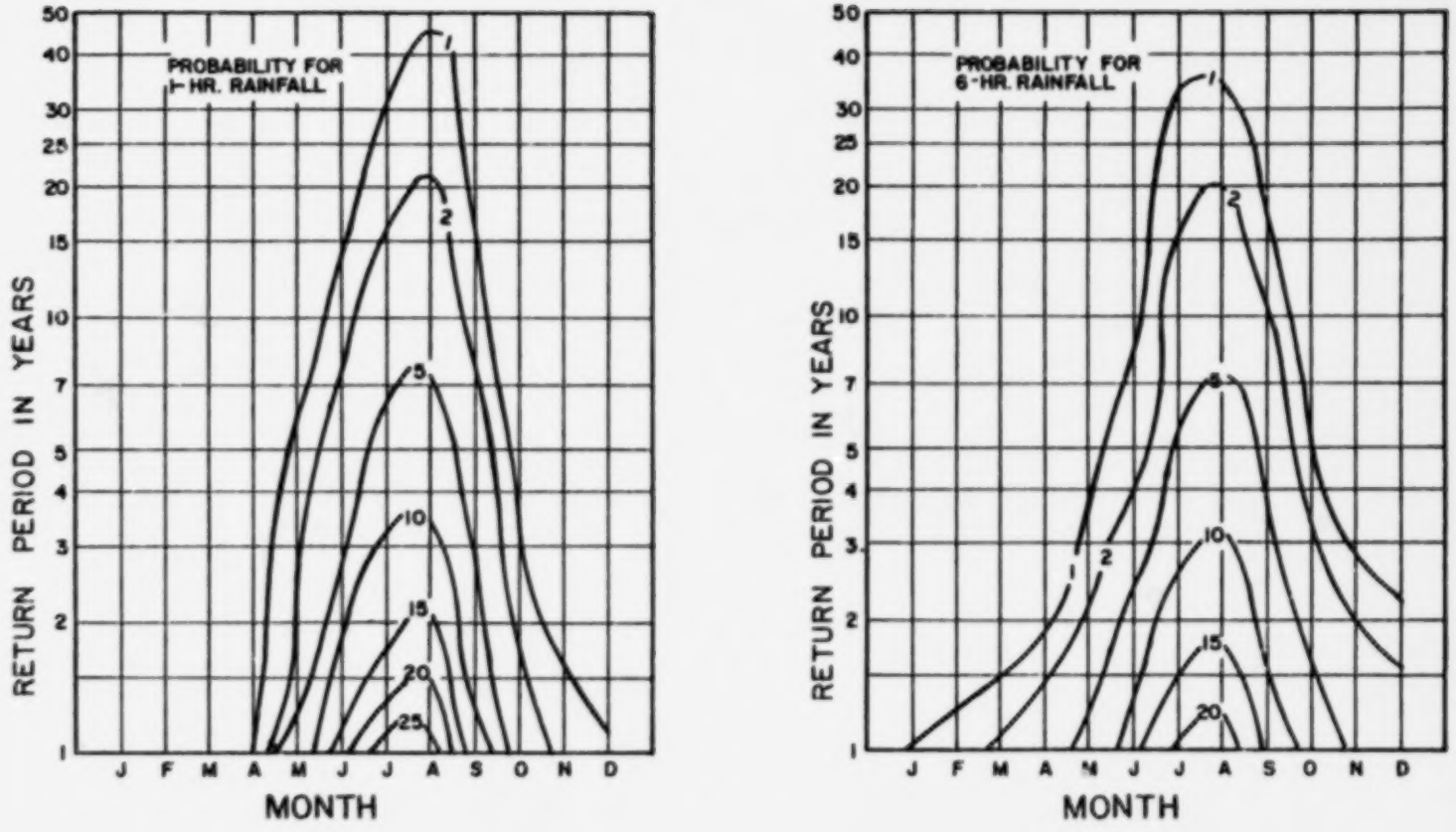


Figure 5. Probability of intense 1-hr and 6-hr rainfall to occur in any particular month.

TABLE 8. RANGE OF D-FACTORS FOR SOME POSSIBLE DESIGN CONDITIONS

Hydrologic group, soil texture and design storm	Minimum infiltration rates (cm/hr)	Rainfall intensity (cm/hr)	D-factor	Total runoff (cm)
D, Clay Loam				
10-yr, 1-hr	0.0 - 0.25	6.6	0.0 - 0.04	6.3 - 6.6
10-yr, 6-hr	0.0 - 0.25	1.7	0.0 - 0.15	8.7 - 10.2
B, Sandy Loam				
10-yr, 1-hr	0.4 - 5.0	6.6	0.06 - 0.76	1.6 - 6.2
10-yr, 6-hr	0.4 - 5.0	1.7	0.24 - 1.0	0.0 - 7.8

SECTION 6

EXPERIMENTAL DESIGN AND PROCEDURES

SYSTEM DESCRIPTION

The field study consisted of measuring rainfall runoff quantity and pollutant concentrations at various distances downslope from an area where caged-layer poultry manure was applied regularly. Runoff was collected, sampled, and then redistributed at each sampling distance. Dimensions of the manure-application areas and nine terraces and the sampler and drainage system placement for the fall and winter (1977-1978) are shown in Figure 6.

The field study was changed somewhat during the spring (1978) to examine intermediate sampling distances. The changes are found in Table 9. Two of the long buffer lengths were changed to shorter lengths by adding two more manure-application areas.

TABLE 9. BUFFER-AREA LENGTH/APPLICATION-AREA LENGTH RATIO FOR RUNOFF COLLECTED AT DOWNSLOPE SIDE OF THE VARIOUS TERRACES

Terrace	Ratio of buffer-area length to application-area length	
	For fall and winter	For spring
1	0.30	0.30
2	1.60	1.60
3	Control	Control
4	0.23	0.23
5	1.40	0.50
6	2.57	0.75
7	0.00	0.00
8	1.00	1.00
9	2.00	2.00

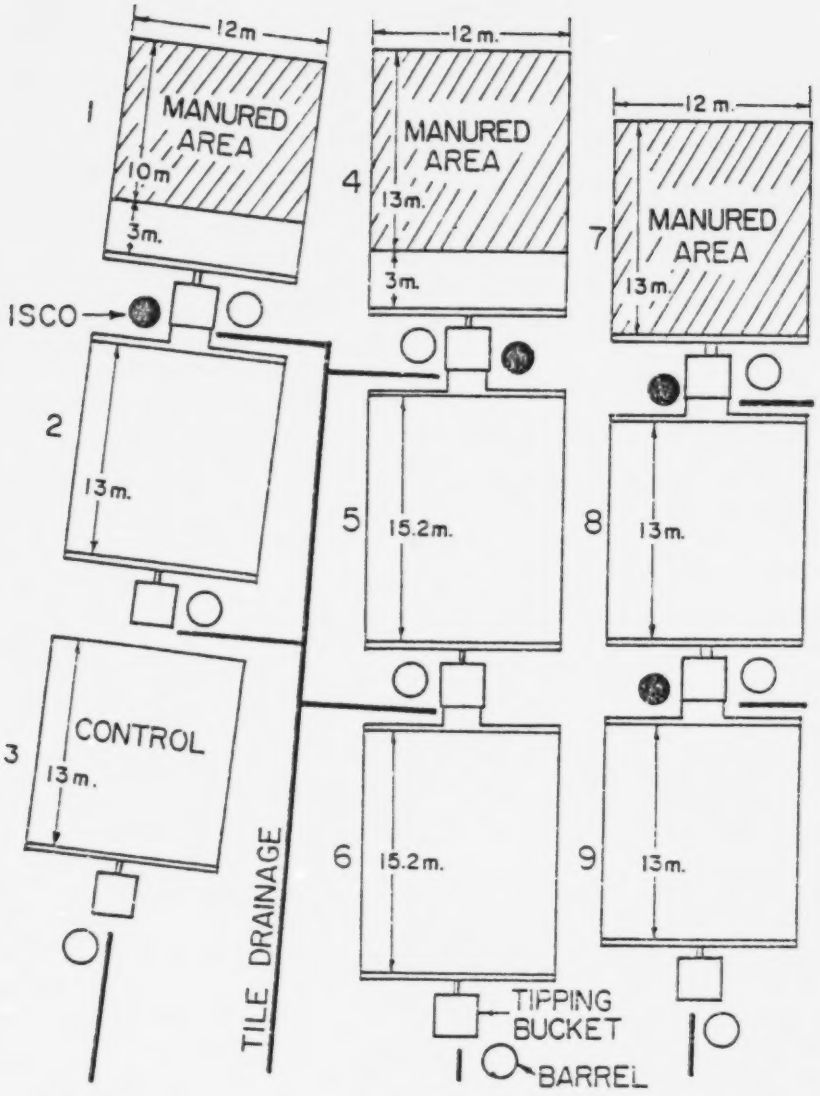


Figure 6. Schematic of application area and buffer zone system during fall and winter.

Rainfall runoff was collected in a gutter at the end of each terrace, passed through a tipping-bucket sampler, and redistributed through a slightly tilted, slotted gutter (Figure 7); or, after runoff passed the last sampling point in each terrace series, it was routed through a tile system away from the plots. Each terrace was bordered by a ditch. The ditches were 40 cm in width and 25 cm in depth. Runoff could not enter the top terrace from upslope or run off the sides of the terraces because of a 25-cm berm around each terrace. Drainage water between terraces was diverted to non-perforated tile drains.

The soil at the buffer-zone site is in the Cecil series, a common soil in the Piedmont subregion of the Southeast. Overcash et al. (1976) found that surface samples of the upper 10 cm were in the clay loam textural class. Subsurface samples were in the clay textural class. When the runoff plots were graded to a uniform slope of 6-8%, the soil horizons were disturbed at the lower end of the plots. These disturbances could affect the infiltration characteristics of the soil.

The plots were seeded with a mixture of reed canarygrass, redtop, and tall fescue in 1974 (Overcash et al., 1976). Fescue has become the dominant grass since initial seeding, with scattered patches of reed canarygrass, redtop, and common bermudagrass.

Approximately two years before the buffer zone study, the plots were used in an overland flow experiment (Overcash et al. 1976). The plots were washed eight times over a nine-month period after the conclusion of the overland flow project. The TKN and P concentrations in the runoff decreased each washing but at a decreasing rate. For instance, flushing samples ranged from TKN concentrations of 9.6 mg/1 and 6.0 mg/1 at the beginning to 2.18 mg/1 and 1.28 mg/1 at the end of the nine-month flushing period. The control plot TKN concentrations during the experiment were consistently higher than the TKN concentrations at the end of the flushing period. The P concentrations for the same period ranged from 4.95 mg/1 and 1.62 mg/1 at the beginning to 1.54 mg/1 and 0.37 mg/1 at the end of the nine-month flushing period. The control plot P concentrations during the experiment were about the same as the P concentrations at the end of the flushing period.

MANURE APPLICATION

Poultry manure was scraped from the alley of a caged-layer house and stored in a side-flail manure spreader for one or two days until a sample could be analyzed to determine the nitrogen content. The poultry manure was applied by a lawn spreader with flow control.

Availability of most nutrients for runoff transport decreases with time after manure application. To determine buffer zone effectiveness during the critical period soon after manure application, several applications were made. Initially, nutrients on the soil surface and grass were measured and summed to determine the total nutrient availability on the plot. However, of the manure applied to the soil-grass complex, nearly 100% was on the grass.

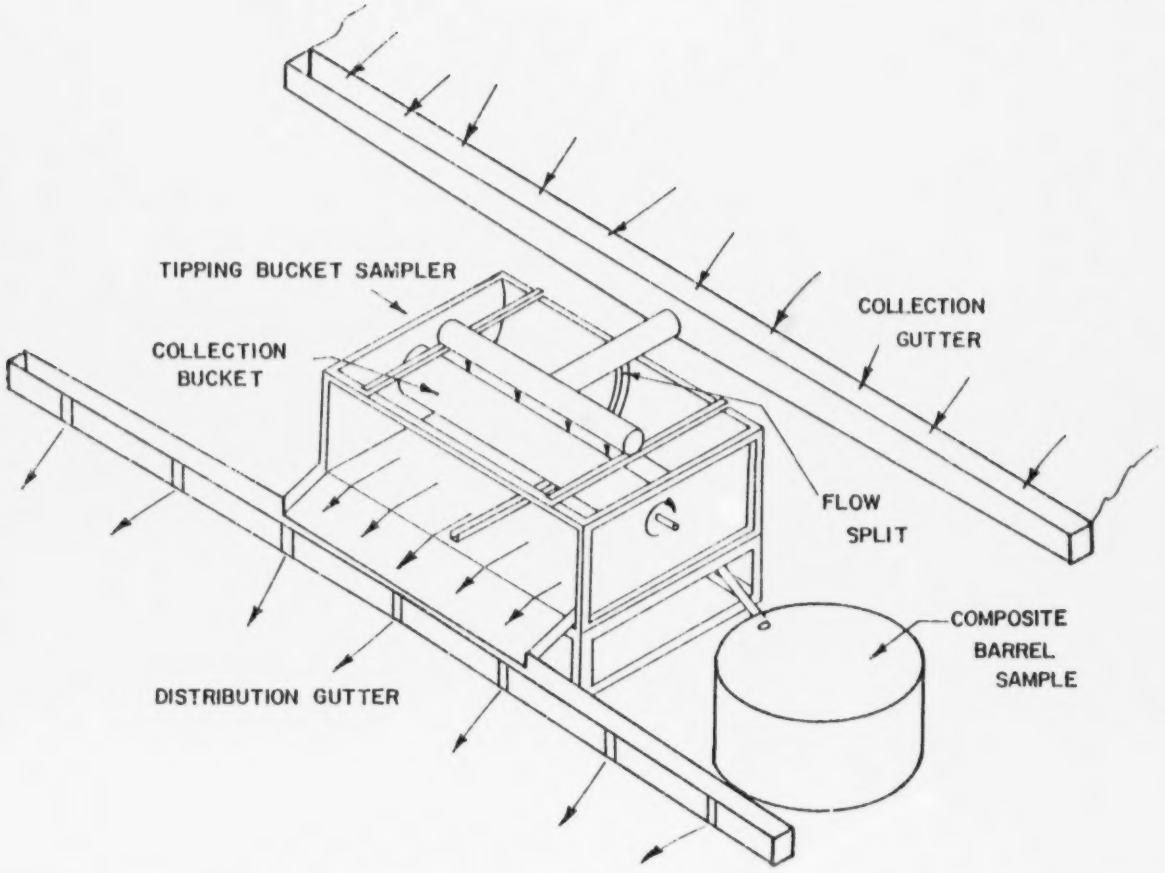


Figure 7. Schematic of flow collector and distributor.

Therefore, grass samples were used in determining the amount of manure to apply and the soil samples were used as a check on nitrogen build-up on the soil surface.

The objective of the grass and soil analysis was to determine the application rate of nitrogen to maintain a uniform load of 100 kg/ha of TKN on the vegetation. Initially, 158 kg TKN/ha was applied and depending on the number of rainfall events, condition of vegetation, and relative build-up of soil nitrogen 30 to 75 kg TKN/ha was applied every two to three weeks depending on availability of manure, weather, and schedule of field personnel. The amount of manure applied was measured by placing 50-by-50-cm plates at three random sections on a terrace divided into 100 equal sections. The measured amount of nutrients applied probably represents a conservative estimate since volatilization, sampling loss, and spreading loss decreased the amount of nutrients in the sample.

GRASS AND SOIL SAMPLING

The terraces were divided into 100 sections 1.2 m by 0.87, 1.0, or 1.3 m, depending on the particular terrace by placing wooden stakes along the edges of the terrace. Random numbers were used to determine from which sections the grass and soil samples would be taken. The first sample in a section was taken in the upper left corner of the plot, and, if that same section was chosen at a later date, the next sample was taken at a position clockwise from the first.

The grass sample at each sampling point was taken with a 23-by-23-cm template. There were three sampling points in each composite sample and two composite samples per terrace both before and after manure was applied. The grass and loose organic material (dead vegetation, etc) on the soil surface were put in plastic bags and taken to the laboratory for analysis. The grass was washed by adding three liters of deionized water to the plastic bag and shaking the bag five minutes at approximately 200 excursion per minute. This was repeated three times to obtain nine liters of wash water. Samples were taken by stirring the wash water and dipping the samples from the center of the container.

Three random 1.9-cm diameter cores of the upper 2 cm of soil were taken at the three sampling points. A preliminary experiment revealed that the 2-cm depth was more effective than a 5-cm depth in detecting nutrient levels near the soil surface. Several soil samples of the surface 2 and 5 cm were taken before and after manure was applied and on the fourth and seventh day after manure was applied. The concentration of TKN was higher in the surface 2 cm than in the surface 5 cm. Increasing the sampling depth resulted essentially in a constant amount of manure being mixed with a greater amount of soil. Even though the 2-cm depth sample was more sensitive to nutrient additions to the soil surface, small deviations from the 2-cm sampling depth may also result in large errors in soil nitrogen measurements. Since depths could be sampled only to plus or minus 0.5 cm and the antecedent moisture content of the soil affected the soil sampling procedure, it was

concluded that soil sampling could be used only as a check for a relative buildup of soil TKN.

RAINFALL-RUNOFF CHARACTERIZATION

Rainfall was measured at the site with a tipping-bucket rain gage and an event recorder. Below each terrace, a composite runoff volume was obtained by collecting approximately 200 ml from each tip of the 5-liter tipping buckets. For runoff collection, barrels, 208 liters in volume, were partially buried at each sampling station and a 114-liter plastic barrel was placed inside each large barrel. After each rainfall event, barrels containing runoff were stirred thoroughly before two composite samples were taken from the middle of the barrel. Composite samples were taken to the laboratory where they were refrigerated or frozen until the laboratory analysis was complete.

Runoff volumes were determined by recording the number of bucket tips on a mechanical counter. Runoff volumes were sometimes difficult to quantify, because the tipping bucket occasionally malfunctioned. Still, runoff volumes were recorded on part of the terraces for most runoff events.

LABORATORY SAMPLE ANALYSIS

Pollution parameters measured in runoff water samples included TKN (not including nitrate), NO_3-N, P, TOC, ammonia nitrogen (NH_3-N) orthophosphate phosphorus (O-PO_4-P), chemical oxygen demand (COD), and chloride (Cl^-). Some samples were analyzed for volatile solids (VS) and total solids (TS). Procedures in Standard Methods (1971) were used for VS, TS, COD (dichromate reflux method) and TOC (Beckman Model 915 TOC Analyzer). The other parameters were analyzed using industrial procedures for the Technicon Auto Analyzer II (Technicon Industrial Systems, Tarrytown, New York).

Grass samples were analyzed for N and P using a sulfuric acid-salicylic acid digestion and the Technicon Auto Analyzer II.

Soil samples were analyzed for TKN using a sulfuric acid-catalyst mixture digestion and the Technicon Auto Analyzer II (modification of procedure used by Schuman et al., 1973).

Detailed procedures of all analyses are given by Bingham (1978).

SECTION 7

RESULTS AND DISCUSSION

INTRODUCTION

The pollution potential of the manured areas was maintained at a relatively high level by frequent application of poultry manure. The effectiveness of grass buffer zones in reducing pollution in runoff from the manured areas was evaluated mainly by measuring pollutant concentration reduction in runoff at various distances downslope of the manured areas. Runoff pollutant concentrations measured for each terrace varied throughout the study because of a number of factors. Concentration of the manured area runoff varied depending upon nutrient availability (which was a function of time since manure application and previous rainfall) and rainfall-runoff characteristics of the storm event. The pollutant concentrations in runoff at various distances downslope of the manured area depended on rainfall-runoff characteristics, and the effectiveness of pollutant removal mechanisms such as settling, "filtering" by vegetation, and infiltration. Normally, the pollutant concentration of a composite sample from the whole runoff event was used for evaluating buffer zone effectiveness, but some results on concentration variation with time during the initial period of runoff are presented to indicate how the initial "flush" of pollutants compared with the average runoff concentration for the whole event.

MANURE APPLICATION RESULTS

Frequent manure applications resulted in a relatively high and uniform amount of manure load on the application area throughout the study, and this allowed the evaluation of buffer zone effectiveness under high pollution potential. The characteristics of the applied poultry manure are given in Table 10. The amounts of material applied to the manure areas as determined by plate collection samples are given in Table 11. Since most of the manure adhered to the vegetation when applied, grass washings were made before and after manure was applied to determine the amount of nutrients on the vegetation available for rainfall-runoff transport. The amounts of nutrients applied versus the amounts washed from grass samples are given for seven applications in Table 12. Soil samples were also taken to keep a check on nutrient build-up in the soil surface zone.

Grass TKN Versus Time with Various Loading Events

The amounts of TKN (kg/ha) washed from the grass collected from the manured area and the control area are plotted against the days of the study

TABLE 10. CHARACTERISTICS OF POULTRY MANURE FROM MECHANICAL SCRAPED CAGED-LAYER HOUSE

Date	TKN	P	COD	TOC	NH_3-N	O-PO_4-P	Cl^-	TS*	VS*
				mg/ℓ					
8-23-77	9,750	3,010	129,000	19,700	6,200	1,220	1,190	--	--
9-29-77	10,450	2,740	122,000	23,700	4,800	1,030	1,530	--	--
10-12-77	12,900	3,030	129,000	38,200	7,650	850	1,580	--	--
11-2-77	13,500	5,860	121,000	38,200	4,400	1,110	920	--	--
11-21-77	15,600	3,900	112,000	28,900	2,100	750	1,760	--	--
12-15-77	10,000	1,840	97,000	35,500	6,000	1,340	1,180	--	--
1-5-78	15,550	4,410	216,000	48,700	2,350	1,920	2,240	--	--
1-27-78	11,600	2,700	163,000	13,200	850	1,030	1,470	--	--
4-21-78	13,150	4,420	184,000	27,600	7,200	1,820	2,370	--	--
5-5-78	12,250	4,510	213,000	22,400	7,500	1,840	3,710	208	138
5-17-78	12,100	3,750	159,000	22,400	4,400	1,740	2,820	--	--

*Units are mg solids per g wet weight of raw manure.

TABLE 11. AMOUNT OF MATERIAL APPLIED TO THE MANURE-APPLICATION AREAS AS DETERMINED BY PLATE COLLECTION*

Date	TKN	P	COD	Cl^-	TOC
	kg/ha				
8-23-77	158	31	1,833	26	194
9-29-77	78	23	923	11	155
10-12-77	35	8	384	5	47
11-2-77	53	12	480	5	112
11-21-77	31	6	259	4	47
12-15-77	70	19	991	9	113
1-5-78	28	9	376	4	36
1-27-78	69	19	847	7	117
4-21-78	80	24	1,028	14	140
5-5-78	60	22	816	14	145
5-17-78	60	24	741	12	167
Total	722	197	8,678	111	1,273

*Average of three plots.

TABLE 12. AMOUNT OF NUTRIENTS APPLIED VERSUS THE AMOUNT OF NUTRIENTS WASHED FROM THE GRASS

Date	TKN		P		COD		TOC		Cl^-	
	Measured on grass	Amount applied	Measured on grass	Amount applied	Measured on grass	Amount applied	Measured on grass	Amount applied	Measured on grass	Amount applied
	kg/ha									
11-21-77	31	31	10	6	474	259	139	47	17	4
12-15-77	82	70	25	19	1,153	991	244	113	10	9
1-5-78	11	28	5	9	215	376	30	36	2	4
1-27-78	28	69	10	19	566	847	76	117	2	7
4-21-78	62	80	27	24	904	1,028	186	140	15	14
5-5-78	35	80	13	22	638	816	157	145	12	14
5-17-78	58	60	26	24	904	741	180	167	21	12
Total	307	398	116	123	4,854	5,058	1,012	765	63.7	64

in Figure 8. The sudden increase in the pollution potential of TKN corresponds to the application dates. Of the 398 kg TKN/ha applied, as measured by the 50-cm by 50-cm plate collection (Table 12), 307 kg TKN/ha was washed from the grass immediately after manure application; hence 77% of the manure ended up on the grass in a form capable of being washed off. The 23% that was unaccounted for was either on the ground, not washable, volatilized, or taken into the leaves.

The TKN amount on the grass is represented in Figure 8 as the difference in the sudden increase in TKN on the grass in the manure-application area. It is apparent that most of the TKN applied is either washed from the grass by rainfall or lost by some other mechanism between rainfall events since build-up of TKN on the grass was minor. Possible pathways of TKN loss include manure drying (i.e. manure adhering to the grass so that it would not wash off), ammonia volatilization (very likely since 40% of TKN applied is NH_3-N, Table 10), nitrification (not likely since NO_3-N was not found on the grass), and grass uptake (nutrients are taken up through the plant foliage).

For the first and second sampling dates after manure application (days five and 11), the data show a large decrease in TKN even though no rainfall occurred. Also, the data show a large decrease in TKN between sampling days 243-246 during a dry period. Reduction in TKN due to losses other than rainfall obviously affects the amount of TKN available for runoff signifying the importance of time of manure application in relation to time of rainfall in determining pollution potential.

Analysis of grass for N after washing the grass directly following manure applications usually showed an increase in the mg N/g dry grass indicating the washing process did not remove all the N applied (Table 13). Also, as the time progresses without a rainfall, a larger amount of N becomes unwashable from the grass as shown by the increase in mg N/g dry grass from 4-21 to 4-24 (Table 13). The increase in N is due to nutrient uptake by the leaves or the N adhering to the grass in an unwashable form.

Soil TKN Versus Time with Various Loading Events

Since the soil TKN of the surface soil was so variable, a large number of samples were taken and averaged together. The kg/ha of soil TKN in the surface 2 cm is plotted against time for the manure-application areas and the control area in Figure 9. The manured area usually shows a much higher level of soil TKN. Apparently, a large amount of the TKN removed from the grass by the rainfall remained on the soil surface.

Grass P Versus Time with Various Loading Rates

The mass of P, kg/ha, measured on the grass during the study is shown in Figure 10. The results are very similar to the TKN analysis inasmuch as the P level on the grass drops between manure applications. The amount of rainfall probably has the greatest effect on the amount of P on the grass since the data show a build-up of P on the grass during the relative dry

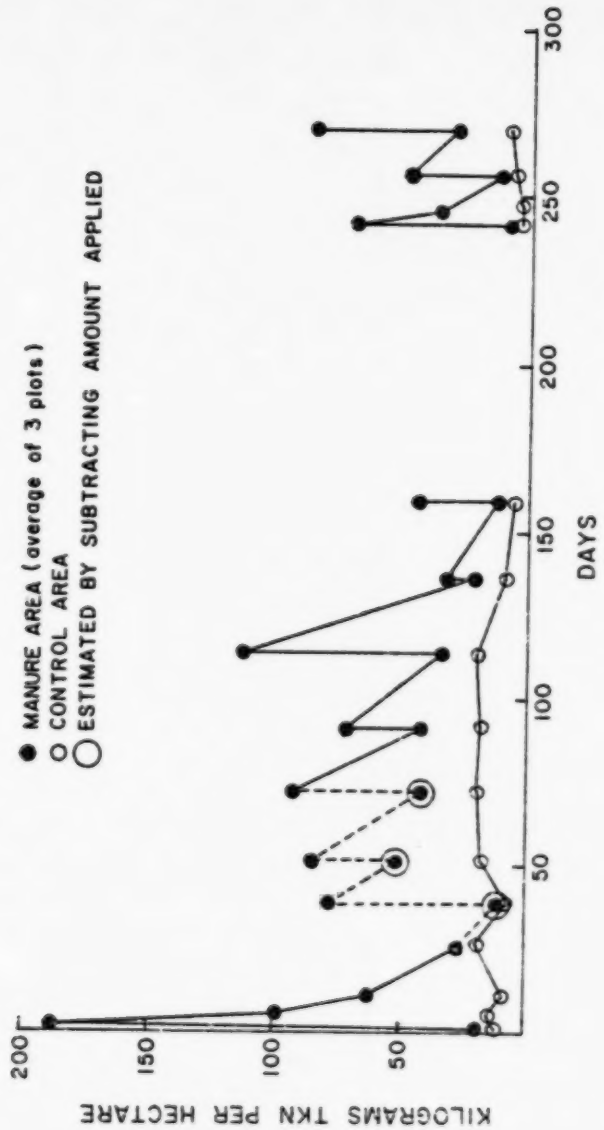


Figure 8. Amount of TKN on grass as determined from grass sample washings.

TABLE 13. N ANALYZED WITH THE GRASS AND WASHED FROM THE GRASS

Plot	Date	Grass analysis before manure applied and after grass washed (mg N per g dry grass)	Change in grass analysis after manure applied and after grass washed (mg N per g dry grass)	Amount Washed from Grass		Percent* N applied not available for washing
				Before manure applied (mg TKN per g dry grass)	After manure applied (mg TKN per g dry grass)	
1	4-21-78	31.65	+3.60	5.6	38.0	10.0
	4-24-78	--	+6.00	--	15.4	--
	5-5-78	29.1	+2.40	4.9	18.1	15.3
	5-17-78	33.75	-5.78	4.7	24.3	-22.8
4	4-21-78	28.35	-0.30	4.7	31.2	-1.1
	4-24-78	--	+0.52	--	15.9	--
	5-5-78	21.38	+4.55	8.5	21.3	26.2
	5-17-78	26.48	+0.37	5.4	23.5	2.0
5	4-21-78	19.35	+0.15	3.3	32.0	0.5
	4-24-78	--	+5.25	--	15.2	--
	5-5-78	20.6	+4.75	5.4	17.7	27.9
	5-17-78	22.65	-3.80	9.5	20.0	-26.6
6	4-21-78	18.05	+2.40	2.8	28.6	8.5
	4-24-78	--	+3.68	--	13.3	--
	5-5-78	21.23	+0.15	6.7	14.0	2.0
	5-17-78	22.20	+6.15	7.1	24.2	26.5

(Continued)

TABLE 13 (continued)

Plot	Date	Grass analysis before manure applied and after grass washed (mg N per g dry grass)	Change in grass analysis after manure applied and after grass washed (mg N per g dry grass)	Amount Washed from Grass		Percent* N applied not available for washing
				Before manure applied (mg TKN per g dry grass)	After manure applied (mg TKN per g dry grass)	
7	4-21-78	32.4	-2.55	3.6	34.5	-7.6
	4-24-78	--	+7.43	--	10.8	--
	5-5-78	37.43	-4.05	2.8	30.3	-12.8
	5-17-78	37.50	-1.27	20.0	32.6	-9.1
Con-	4-21-78	19.05	--	3.07	--	--
trol	4-24-78	20.30	--	3.07	--	--
	5-5-78	31.65	--	2.21	--	--
	5-17-78	18.74	--	3.90	--	--
					Average Percent	2.6

*Percent--(the change in grass analysis after manure applied and after grass washed) divided by the sum of the difference in (the amount washed from grass) and (the change in grass analysis after manure applied and after grass washed).

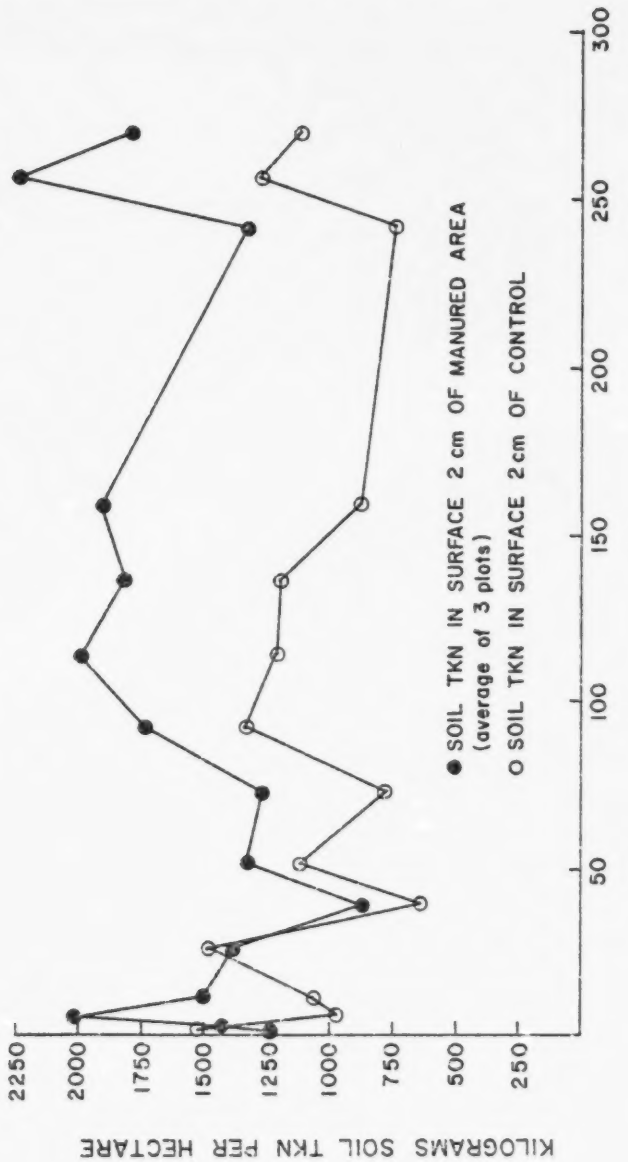


Figure 9. Soil TKN in the surface 2 cm.

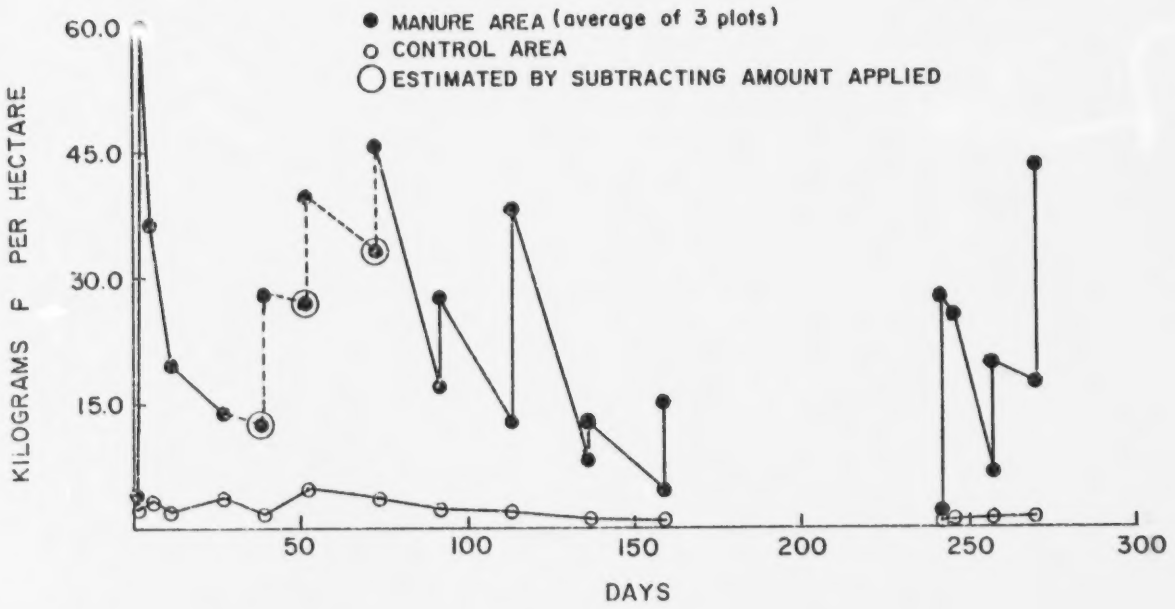


Figure 10. Amount of P on grass.

part of the year from days 50-100. P also exhibits a drop after manure applications even though it did not rain during some periods. Seemingly, P becomes unaccessible for washing by the drying process and/or plant uptake. The grass analysis revealed that immediately after manure is spread and washed from the grass, an increase in the mg P/g dry grass occurred (Table 14), indicating part of the P became absorbed to the grass very quickly. P became even more unavailable to the washing process from 4-21 to 4-24 (Table 14). The results presented in Table 12 indicate that 94% of the P is washable off the grass immediately after application. Apparently the 6% not available for washing (100-94) is on the grass because for the three applications in Table 14 an average of 8.1% of the P is determined to be unavailable for washing (i.e. adsorbed to grass).

Grass COD and TOC Versus Time with Various Loading Rates

COD and TOC on the grass were estimated from grass washings during the study and results are shown in Figures 11 and 12. The results are similar to the TKN and P behavior discussed previously. The COD and TOC levels are likewise reduced by losses besides rainfall. However, rainfall is the most important factor as evidenced by the build-up of COD and TOC during the dry part of the year (days 50-100). Ninety-six percent of the COD and all of the TOC is accounted for by the grass washings suggesting most of the manure is on the grass initially (Table 12).

Grass Cl^- Versus Time with Various Loading Rates

The Cl^- on the grass during the study is shown in Figure 13. The effectiveness of the grass washings is demonstrated by the relatively constant level of Cl^- during the periods that it did not rain (days 2-11 and 243-246). Even small rainfall events reduced the Cl^- level to background levels as shown by the sample washings made before the manure is applied throughout the study. Essentially all of the Cl^- applied is measured in the grass washings immediately after application (Table 12).

POTENTIAL AMOUNT OF POLLUTANTS FILTERED FROM RUNOFF

Runoff samples from three runoff events were studied to assess the nature of the runoff material transported from the manure-application/buffer zone system. The three events which were used occurred on 1-8-78 (2.56 cm rain), 1-17-78 (2.08 cm rain) and 1-19-78 (4.42 cm rain). A 150-ml sample of runoff from each of the nine terraces was divided in half using a 25-ml automatic pipetter while being stirred with a magnetic stirrer. Alternate 25-ml portions of the runoff sample were placed in a clean bottle or filtered through Whatman 41, ashless, filter paper. This filter paper filters course and gelatinous precipitates out of runoff samples. The filtered and non-filtered runoff samples were stored in a refrigerator until COD, TKN, P, $O\text{-}PO_4\text{-}P$, $NO_3\text{-}N$, and Cl^- could be determined.

After the runoff samples were analyzed, the results were normalized by combining the filtered and nonfiltered samples in the following manner:

TABLE 14. P ANALYZED WITH THE GRASS AND WASHED FROM THE GRASS

Plot	Date	Grass analysis before manure applied and after grass washed (mg P per g dry grass)	Change in grass analysis after manure applied and after grass washed (mg P per g dry grass)	Amount Washed from Grass		Percent* P applied not available for washing
				Before manure applied (mg P per g dry grass)	After manure applied (mg P per g dry grass)	
1	4-21-78	3.90	+0.45	1.3	16.5	3.0
	4-24-78	--	+1.42	--	10.4	--
	5-5-78	5.32	-0.21	2.5	7.6	-3.9
	5-17-78	7.95	+0.15	3.3	11.4	1.8
2	4-21-78	3.15	+1.27	1.0	14.4	8.7
	4-24-78	--	+2.18	--	10.9	--
	5-5-78	2.40	+1.90	2.7	10.6	19.4
	5-17-78	5.10	+0.90	2.5	10.6	10.3
5	4-21-78	3.30	-0.07	0.5	11.6	-0.6
	4-24-78	--	+1.20	--	10.7	--
	5-5-78	3.03	+1.20	2.6	7.0	21.3
	5-17-78	4.88	+0.22	7.4	11.0	5.8
6	4-21-78	2.40	+0.30	0.4	10.4	2.9
	4-24-78	--	+2.40	--	9.2	--
	5-5-78	3.38	+0.45	3.2	5.4	17.0
	5-17-78	4.65	+0.75	5.0	11.5	10.3

(Continued)

TABLE 14 (continued)

Plot	Date	Grass analysis before manure applied and after grass washed (mg P per g dry grass)	Change in grass analysis after manure applied and after grass washed (mg P per g dry grass)	Amount Washed from Grass: Before manure applied (mg P per g dry grass)	Amount Washed from Grass: After manure applied (mg P per g dry grass)	Percent* P applied not available for washing
7	4-21-78	3.60	+1.13	0.6	12.3	8.8
	4-24-78	--	+1.20	--	7.0	--
	5-5-78	5.70	+0.45	1.4	11.1	4.4
	5-17-78	6.23	+0.98	9.8	16.9	12.1
Con-	4-21-78	2.25	--	0.32	--	--
trol	4-24-78	2.95	--	0.45	--	--
	5-5-78	4.55	--	0.28	--	--
	5-17-78	3.23	--	0.52	--	--
					Average Percent	8.1

*Percent--(Change in grass analysis after manure applied and after grass washed) divided by the sum of the difference in (the amount washed from grass) and (the change in grass analysis after manure applied and after grass washed).

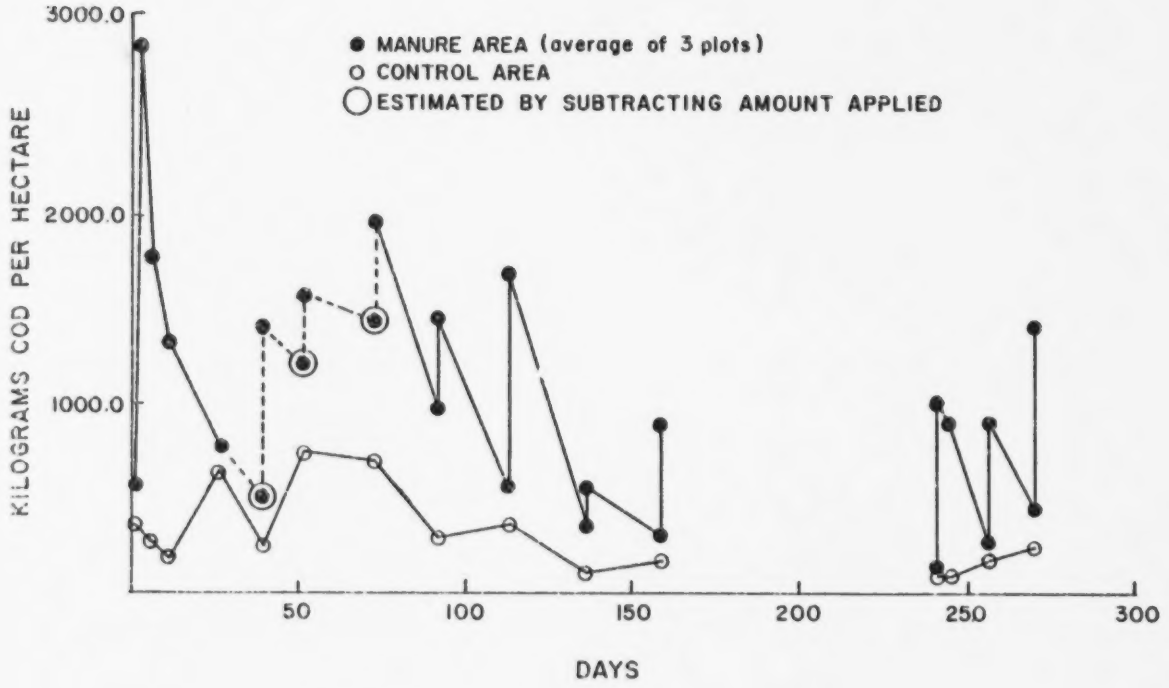


Figure 11. Amount of COD on grass.

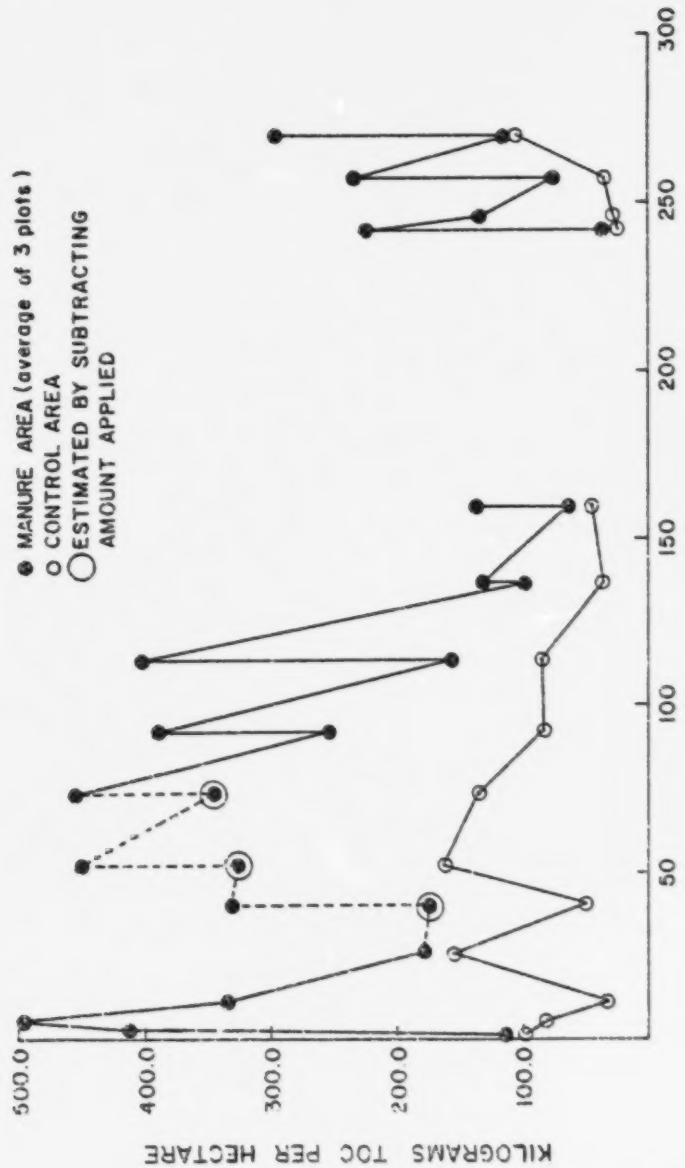


Figure 12. Amount of TOC on grass.

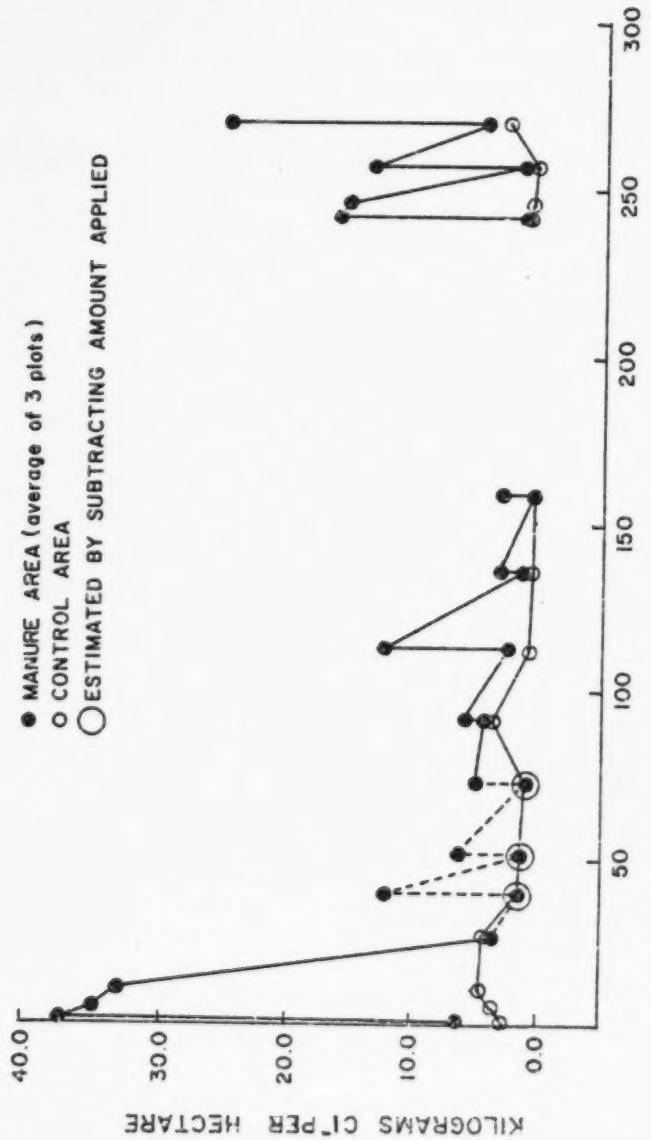


Figure 13. Amount of Cl^- on grass.

$$\frac{\text{COD nonfiltered-COD filtered}}{\text{COD nonfiltered}}$$

There was a need to normalize the results since a large difference in filtered and nonfiltered samples could be the effect of filtering a lot of solids or due to the variation in concentration in the samples. The mean of the normalized parameters multiplied by 100 represents the percent reduction by filtering. The results are shown in Table 15.

TABLE 15. PERCENT REDUCTION OF POLLUTANTS BY FILTERING OF RUNOFF SAMPLES

Pollutant	% reduction by filtering
COD	16.9*
TKN	26.5**
P	33.6**
$O\text{-}PO_4\text{-}P$	18.3**
$NO_3\text{-}N$	3.4
Cl^-	0.0

*Significantly different from 0.0% at 5% level.

**Significantly different from 0.0% at 1% level.

The COD, TKN, P, and $O\text{-}PO_4\text{-}P$ in the filtered samples were shown to be significantly different from the nonfiltered samples even though the percent reductions were somewhat low. This probably indicates that most of the samples contained similar amounts of filterable solids. The results indicate that large percentages of the materials were not easily filtered out, especially $NO_3\text{-}N$ and Cl^-, which were expected to be soluble. The TKN, P, $O\text{-}PO_4\text{-}P$, and COD were probably non-adsorbed or adsorbed to small clay particles, etc. which were suspended in the runoff samples and filtered through Whatman 41 filter paper.

Since the filter paper chosen is probably more effective than the grass canopy "filter", the filter paper method gives only an estimate of the maximum amount of pollutants which could be filtered from runoff. The ability of vegetation to physically filter runoff through the buffer area may not be one of the more important factors in the reduction of the pollution potential since a large percentage of the nutrients were soluble and suspended and not easily filtered. This indicates that a large part of the pollutants from manure-application areas are soluble or small suspended particles which are easily carried along with the water.

TRENDS IN CONCENTRATIONS IN RUNOFF WITH TIME DURING A RUNOFF EVENT

Automated samplers were used to take 28 discrete samples at the beginning of the runoff event on four of the runoff terraces. Since the tipping buckets occasionally tipped faster than the sampler pumping cycle, the exact number of tips per discrete sample was not known. Judging from the volumes of the discrete samples, the bucket usually tipped from one to six times during the pumping cycle. Nevertheless, trends in concentration with time were determined even though the time increments were not distinct.

Evidence of an initial flush may be detected by comparing the composite sample to the discrete samples taken at the beginning of the runoff event. The composite samples contained samples taken throughout the entire event while the discrete samples were collected for the first 1 to 3 mm of runoff. Tables 16-20 show the comparison between composite and discrete samples and trends within the discrete samples.

Generally an increase in COD, TKN, P and Cl^- were noticed for the first discrete sample, but this was mostly due to the pollutants washing out of the sampling system. The first sample was sometimes contaminated because of worms, dead grass, etc. accumulating in the gutters and tipping buckets between rainfall events. A washing of the sampling system verified this first sample phenomenon (Table 21).

The COD and TKN concentrations for the composite samples were usually equal to or slightly greater than the discrete samples indicating no initial flush of these pollutants (Tables 16 and 17). The COD and TKN concentration for the most part were constant in the discrete samples and no trends were found. The composite and discrete data comparison revealed that P sometimes increased in concentration as the rainfall event progressed (Table 18). The P concentrations in the discrete samples increased with time indicating that the runoff from the application area did not reach the sampler initially because of the time it took for the runoff to travel through the buffer zone and/or the P was more available for runoff a little later in the event.

Cl^- and NO_3-N are both highly soluble in water and runoff concentrations would be expected to decrease with time as the amounts available at the surface are depleted by infiltration and runoff. The NO_3-N sample concentrations increased with time for the discrete samples, but had a variable trend when comparing initial runoff to the composite (Table 19) which could indicate a large difference in the amount of NO_3-N present on the plots at different dates due to nitrification. The Cl^- concentration increased with time for the discrete samples and was generally less in the composite sample indicating a decrease in available Cl^- with time (Table 20). Apparently NO_3-N and Cl^- increase in concentration through the initial movements of runoff, and the decrease or increase in concentration as the runoff event continues probably depends upon the amount available for runoff.

TABLE 16. TRENDS IN COD CONCENTRATION DURING RUNOFF EVENTS*

Event	Composite to discrete sample comparison: Buffer area to manured area ratio 0	0.2	0.3	1.0	Discrete sample trends: Buffer area to manured area ratio 0	0.2	0.3	1.0
10-26-77	greater	greater	---	greater	N	N	---	N
11-6-77	less	less	less	---	N	N	N	---
1-8-78	same	---	same	same	N	---	N	N
1-13-78	less	less	same	---	N	N	N	---
1-14-78	same	same	---	---	N	N	---	---
1-17-78	greater	greater	---	---	N	N	---	---
1-19-78	greater	greater	same	same	N	N	N	N
1-25-78	same	greater	greater	less	N	N	N	N

*Note: same - The composite sample concentration was comparatively the same as the discrete samples' concentrations.

greater - The composite sample concentration was larger than the discrete samples' concentrations.

less - The composite sample concentration was less than the discrete samples' concentrations.

--- - No data.

decrease - Discrete sample concentrations were getting smaller with time.

increase - Discrete sample concentrations were getter larger with time.

N - No trends were observed.

TABLE 17. TRENDS IN TKN CONCENTRATION DURING RUNOFF EVENTS*

Event	Composite to discrete sample comparison: Buffer area to manured area ratio 0	0.2	0.3	1.0	Discrete sample trends: Buffer area to manured area ratio 0	0.2	0.3	1.0
10-26-77	same	same	---	greater	N	N	---	N
11-6-77	same	same	same	---	decrease	N	N	---
1-8-78	less	---	same	same	increase	---	N	N
1-13-78	greater	less	greater	---	N	N	N	---
1-14-78	greater	greater	---	---	N	N	---	---
1-17-78	greater	same	---	---	decrease	decrease	---	---
1-19-78	greater	same	greater	same	N	N	N	N
1-25-78	less	less	greater	less	N	N	N	N

*Note: See note below Table 16.

TABLE 18. TRENDS IN P CONCENTRATION DURING RUNOFF EVENTS*

Event	Composite to discrete sample comparison: Buffer area to manured area ratio 0	0.2	0.3	1.0	Discrete sample trends: Buffer area to manured area ratio 0	0.2	0.3	1.0
10-26-77	same	same	---	greater	increase	increase	---	increase
11-6-77	same	same	greater	---	increase	increase	increase	---
1-8-78	same	---	same	same	increase	---	N	N
1-13-78	greater	greater	greater	---	increase	increase	N	---
1-14-78	same	same	---	---	N	N	---	---
1-17-78	same	less	---	---	N	increase	---	---
1-19-78	greater	same	same	less	N	N	N	N
1-25-78	greater	greater	greater	greater	increase	increase	increase	increase

*Note: See note below Table 16.

TABLE 19. TRENDS IN NO_3-N CONCENTRATION DURING RUNOFF EVENTS*

Event	Composite to discrete sample comparison: Buffer area to manured area ratio 0	0.2	0.3	1.0	Discrete sample trends: Buffer area to manured area ratio 0	0.2	0.3	1.0
10-26-77	less	less	---	less	increase	increase	---	increase
11-6-77	same	greater	greater	---	increase	increase	increase	---
1-8-78	same	---	greater	same	increase	---	increase	N
1-13-78	less	less	greater	---	increase	increase	increase	---
1-14-78	same	greater	---	---	N	N	---	---
1-17-78	less	greater	---	---	increase	increase	---	---
1-19-78	less	less	same	less	N	increase	increase	increase
1-25-78	greater	less	greater	greater	increase	increase	increase	N

*Note: See note below Table 16.

TABLE 20. TRENDS IN Cl^- CONCENTRATION DURING RUNOFF EVENTS*

Event	Composite to discrete sample comparison: Buffer area to manured area ratio 0	0.2	0.3	1.0	Discrete sample trends: Buffer area to manured area ratio 0	0.2	0.3	1.0
10-26-77	greater	less	---	same	increase	increase	---	increase
11-6-77	greater	less	same	---	N	N	N	---
1-8-78	less	---	less	less	increase	---	increase	increase
1-13-78	less	less	less	---	decrease	increase	increase	---
1-14-78	greater	greater	---	---	decrease	decrease	---	---
1-17-78	less	less	---	---	N	N	---	---
1-19-78	less	less	same	less	N	N	N	N
1-25-78	less	less	less	greater	N	N	N	N

*Note: See note below Table 16.

TABLE 21. WASHING OF SAMPLING SYSTEM

Discrete sample number*	COD	TKN	P	NO_3-N	Cl^-
	mg/ℓ				
1	439	27.48	3.15	1.8	9.0
2	19	1.26	0.20	1.94	6.0
3	--	0.63	0.12	1.88	6.0
4	--	0.21	0.10	1.9	5.7
5	6	0.36	0.08	1.92	5.9
6	--	0.27	0.08	1.92	5.8
7	--	0.36	0.08	1.9	5.9
8	--	0.30	0.08	1.84	5.7
9	--	0.33	0.08	1.9	5.5
10	6	0.60	0.08	1.9	5.5

*Successive samples; may not be from equal volumes of runoff.

CONCENTRATION REDUCTION RESULTS

The data presented in this section include fall, winter, and spring runoff events. Generally, concentrations for all the parameters measured were greater for small events relative to the large events. Reductions could not be shown with buffer distance when small events were analyzed, inasmuch as concentrations for small events usually varied over a wide range depending on how clean the sampling systems were initially. Therefore, only the large runoff events are discussed. All rainfall events are given in Table 22.

The application of poultry manure caused large increases in runoff concentrations for most pollutant parameters. The average concentrations for nine runoff events for the control (terrace 3) and a similar manured plot with no buffer zone (terrace 7) are shown in Table 23. The largest percent increases in pollution concentrations were for P (613%) and NO_3-N (462%).

TABLE 22. RAINFALL DURING THE EXPERIMENTAL PERIOD

Date	Rainfall (cm)	Date	Rainfall (cm)
9-8-77*	14.4	1-17*	2.1
9-16	1.5	1-19*	4.4
10-1,2	1.4	1-25*	2.8
10-10	1.0	2-2	0.9
10-12,13,14	5.5	2-13	0.3
10-26*	5.5	2-16	0.8
11-2,3	1.4	2-18	0.3
11-4,5	0.5	2-24	0.8
11-6*	4.4	2-28	0.7
11-23	0.1	3-3,4	1.6
11-25	1.3	3-8,9,10	5.3
11-28,29	0.5	3-14	0.2
12-5	0.9	3-27	3.3
12-9	0.3	4-11	0.3
12-14	2.1	4-13	0.8
12-17	0.6	4-17,18,19	4.3
12-20	1.7	4-25	1.9
12-24	0.5	4-26*	12.1
12-30,31	1.1	4-27	0.4
1-6-78	1.6	4-30	0.2
1-8*	2.6	5-4	2.6
1-13,14*	4.3	5-8*	4.3
		5-9	0.5

*Large runoff events.

TABLE 23. CONCENTRATION INCREASES IN RUNOFF DUE TO MANURE APPLICATION*

Runoff plot	Pollutant concentration, mg/l						
	COD	TKN	P	NO_3-N	Cl^-	TOC	VS/TS
Control (terrace 3)	67.8	3.47	0.71	1.69	3.36	18.4	0.19
Manured area with no buffer zone (terrace 7)	96.9	6.88	5.06	9.46	4.03	29.0	0.35
Percent increase due to manure application	43	98	613	462	20	58	84

*Average for 7 to 9 events.

Grass buffer zones downslope of the manured areas decreased concentrations of pollutants in runoff. The average concentrations during the experiment at each buffer-area length/application-area length ratio are shown in Table 24. Generally, concentration of all parameters approached the background area runoff concentration at a buffer-area length/application-area length ratio of 1.0. However, the concentration data for each event is presented in the following sections and shows variability in concentrations from one event to the next. The variation in concentrations from one event to another was affected by the number of days since the last manure application, previous rainfall, and, probably, climatic and seasonal factors. The parameters whose concentrations seemed most affected by length of time since manure application were TKN, P, COD, and TOC, while those affected by amount of previous rain since manure applications were TKN, NO_3-N, P, TOC, Cl^-, and the VS/TS ratio.

TKN Concentration Reduction Through Buffer Zones

The concentration of TKN in runoff is plotted against the buffer-area length/application-area length ratio in Figure 14. In five out of nine events the control has a greater concentration than the runoff from the manured plots at the 1.0 buffer-area length/application-area length ratio. The TKN concentrations in runoff for all ratios greater than 1.0 range from 1.5 - 5.0 mg-TKN/1. Runoff concentrations near the manured area (between 0 and 0.5 ratio) range from 4.0 - 9.0 mg-TKN/1. Obviously there is a difference in water quality when comparing the higher and lower buffer-area length/application-area length ratios. The intermediate ratio range between 0.5 and 1.0 probably is the critical range. There is some evidence indicating that the 0.75 ratio is just as effective as the 1.0 ratio since the two events measured at the 0.75 ratio have a lower concentration than at the

TABLE 24. AVERAGE CONCENTRATION OF RUNOFF POLLUTANTS AT EACH BUFFER-AREA LENGTH/APPLICATION-AREA LENGTH RATIO

Pollutant	Pollutant concentrations, mg/l										
	Buffer-area length/application-area length ratio										
	0	0.2	0.3	0.5*	0.75*	1.0	1.4	1.6	2.0	2.6	Control
COD	97	88	75	96	64	65	62	56	65	66	68
TKN	6.88	5.88	5.60	4.89	3.83	3.03	3.36	2.57	2.84	3.04	3.47
P	5.06	4.66	2.39	2.12	1.34	1.10	1.40	0.83	0.83	0.98	0.71
NO_3-N	9.46	9.12	7.9	0.20	0.10	0.99	1.13	0.82	0.18	0.21	1.69
Cl^-	4.03	4.73	4.27	5.0	3.0	2.81	3.61	3.18	2.38	3.04	3.36
TOC	29	28	26	32	26	19	20	19	19	20	18
VS/TS	0.35	0.33	0.40	0.29	0.22	0.24	0.27	0.21	0.22	0.21	0.19

*For two events; other averages are for 7 to 9 events.

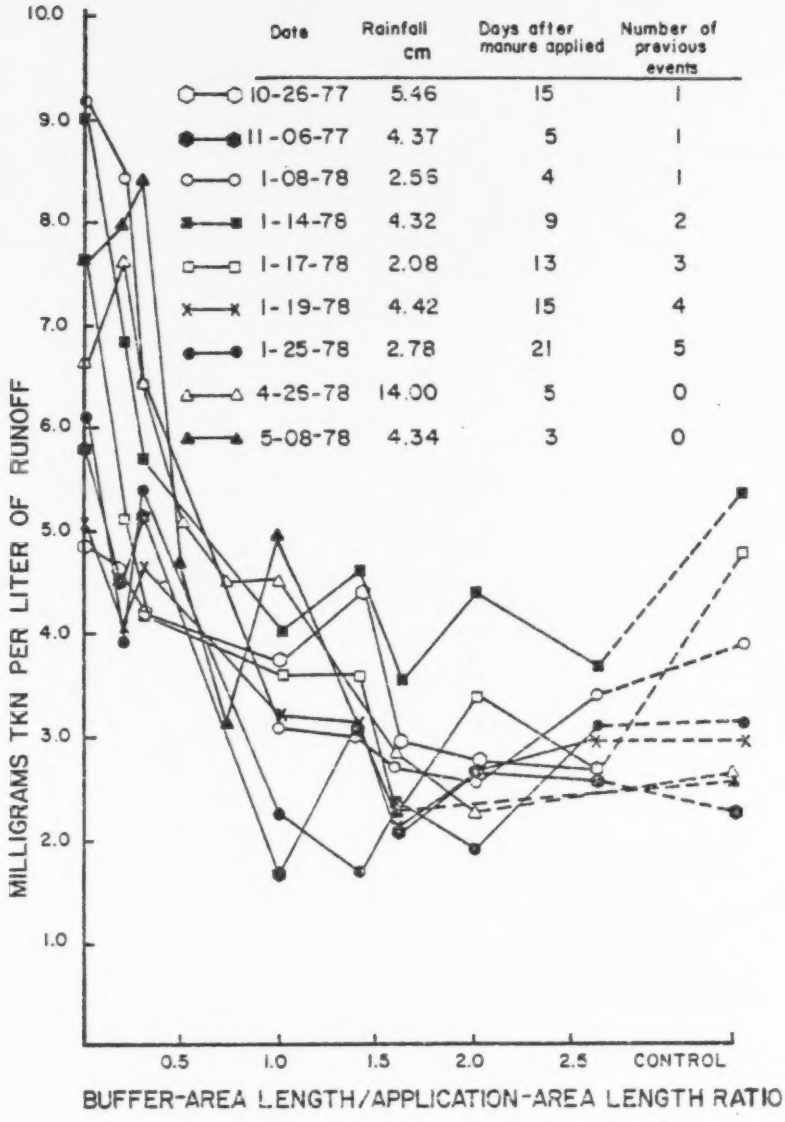


Figure 14. Effectiveness of the grass buffer zone in removing TKN from rainfall runoff.

1.0 ratio. However, a graph of the average concentrations for the events (Figure 15) shows that at least a 0.75 buffer-area length/application-area length is needed to reduce TKN concentration to near that of the control plot.

Many factors are influencing the runoff concentration as shown by the variability in concentration for different events. A major factor is the number of days after manure is applied because the sooner after application large rainfall events occur the less time available for small rains to wash nutrients to the soil surface or for other losses to occur. The greatest runoff concentrations occurred three, four, five, and nine days after the manure application as compared to runoff events occurring five, 13, 15, and 21 days after manure application in Figure 14. Also, the lower concentration for five days after application (for 11-6-77) occurred after a previous rainfall. Probably the most evident trend is the effect of previous rains on runoff concentrations. Rainfall events 1-8-78 through 1-25-78 are such a series of events. Each progressive rainfall event, the runoff concentration generally decreases an increment. No obvious trends are shown between rainfall amounts and TKN concentration.

The NH_3-N/TKN ratios for the 4-26-78 event are presented in Table 25. The NH_3-N/TKN ratio ranged from 0.04 to 0.32, generally decreasing as the buffer-area length/application-area length ratio increased. A possible explanation is that NH_3-N is loss through volatilization as well as infiltration and organic-N is not lost at as great a rate.

TABLE 25. NH_3-N/TKN RATIO VERSUS BUFFER-AREA LENGTH/APPLICATION-AREA LENGTH RATIO*

Buffer-area length/ application-area length ratio	NH_3-N	TKN	NH_3-N/TKN
0.0	2.10	6.60	0.32
0.2	2.10	7.56	0.28
0.3	1.38	6.42	0.21
0.5	1.32	5.10	0.26
0.75	0.72	4.50	0.16
1.00	0.18	4.35	0.04
1.60	0.30	2.85	0.10
2.00	0.12	2.25	0.05
CONTROL	0.30	2.67	0.11

* Data for runoff event of April 26, 1978.

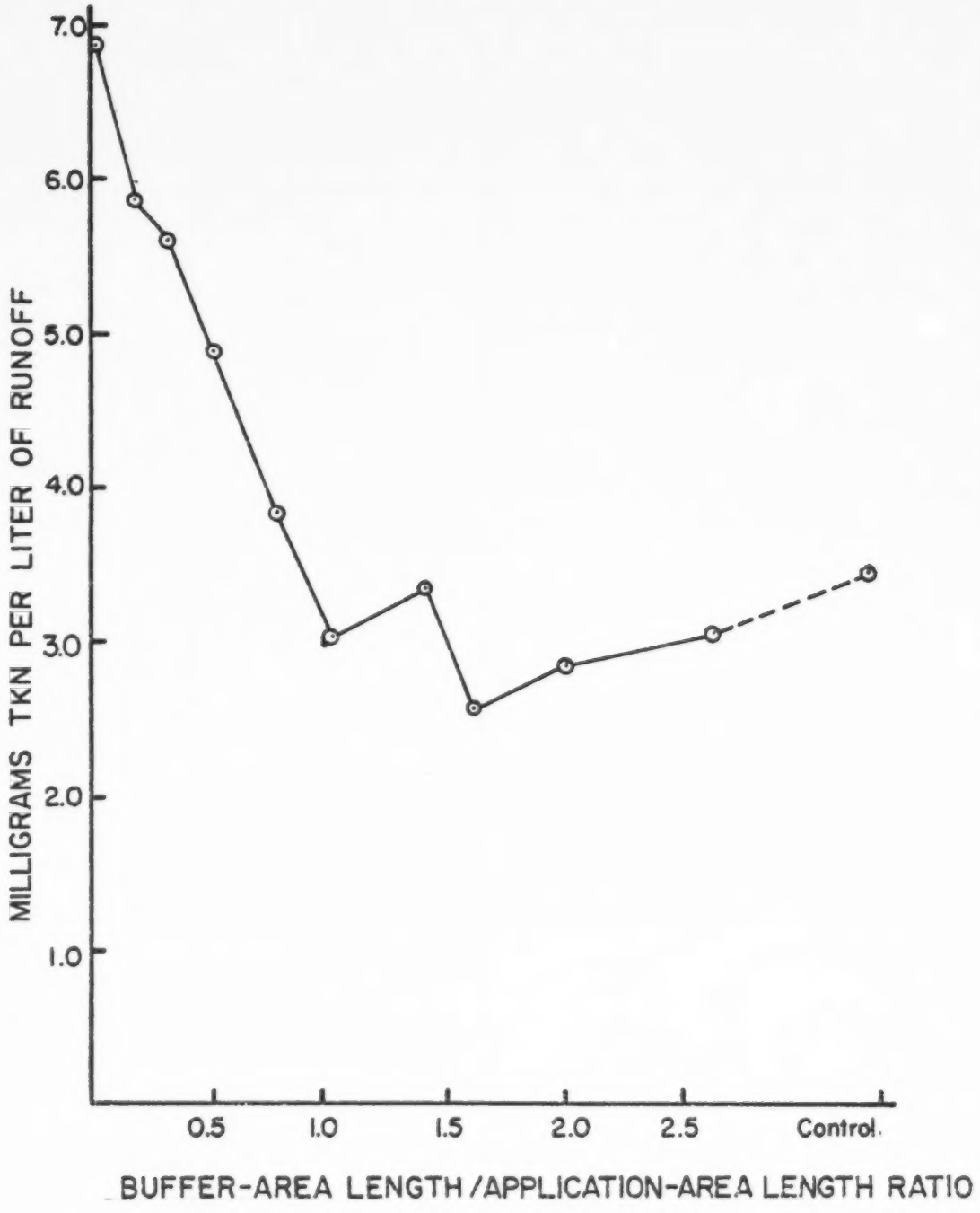


Figure 15. Average TKN concentrations for the various buffer-area length/application-area length ratios.

NO_3-N Concentration Reduction Through Buffer Zones

In Figure 16 the mg of NO_3-N per liter of runoff is plotted against the buffer-area length/application-area length ratio. The effectiveness of buffer zones in eliminating the pollution potential is explicitly shown by the amount of NO_3-N reduction measured. The data show that the highest runoff concentration occurred during January when the ground is typically saturated and frozen. Runoff concentrations of NO_3-N are nearly four times higher in January than in May even though the number of days after manure application are nearly the same. One possible difference is infiltration since the infiltration rate during winter is small compared to that during the spring because of the soil freezing. Another possible reason for greater concentrations in January is the greater frequency of manure loadings in the months previous to January as compared to the months previous to May.

Again, the control plot often exceeded the application-area NO_3-N concentration at distances greater than the 1.0 buffer-area length/application-area length ratio. There is some evidence indicating that the 0.5 and 0.75 buffer-area length/application-area length ratios are just as effective as the 1.0 ratio in eliminating the pollution potential since the runoff concentrations are approximately the same. In fact, the average NO_3-N concentrations for the events (Figure 17) show some increase after the 0.5 buffer-area length/application-area length ratio.

The number of previous rains generally reduces the NO_3-N concentration (Figure 16). This is not always the case, especially for rainfall events 1-14-78 and 1-17-78. Since the 1-17-78 rainfall event has a greater NO_3-N concentration, it is speculated that the rainfall amount may also be influencing the runoff concentrations of NO_3-N. This is probable since the NO_3-N concentration usually decreases as rainfall continues; therefore, larger rainfalls have more dilution effect when evaluating the total event.

P Concentration Reduction Through Buffer Zones

The mg/ℓ of P measured in the runoff during the experiment is found in Figure 18. The reduction in P is not as variable as other pollutants measured. The P concentration in runoff is practically constant for buffer-area length/application-area length ratios greater than 1.0. The P concentrations at the 0.5 and 0.75 buffer-area length/application-area length ratios are somewhat higher than at the 1.0 ratio indicating reductions are still likely at these points. A plot of the average P concentrations for these events (Figure 19) also clearly shows this. The number of days after the manure applications also affects the magnitude of the runoff concentration since rainfall events 1-8-78, 1-14-78, and 4-26-78 have relatively high runoff concentrations from the manured area.

$O\text{-}PO_4$-P and P were measured for several of the events (Table 26). The $O\text{-}PO_4$-P/P ratio is usually greater than 0.9 when P concentrations are greater than 2 mg/1, but is variable at lower concentrations. Since the difference between P and $O\text{-}PO_4$-P concentrations usually remains between 0.1 mg/1 and 0.5 mg/1, the large changes are due to $O\text{-}PO_4$-P contributed by the

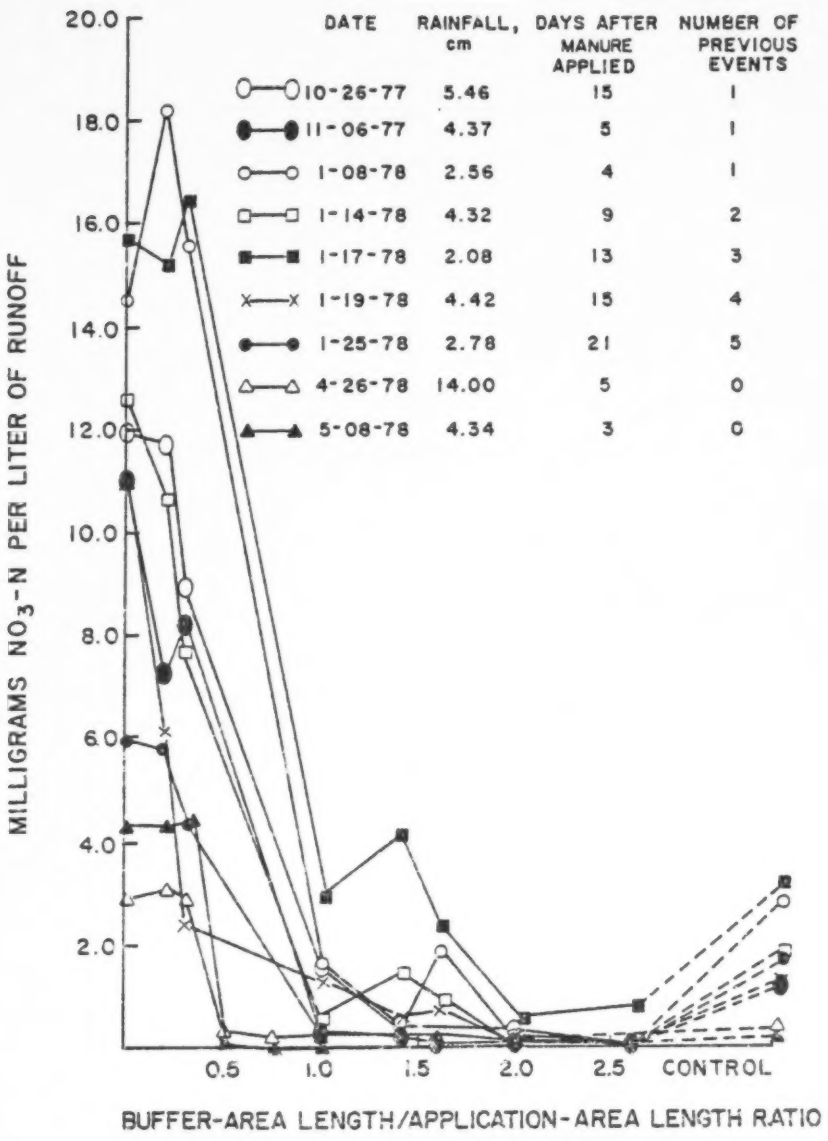


Figure 16. Effectiveness of the grass buffer zone in removing NO_3-N from rainfall runoff.

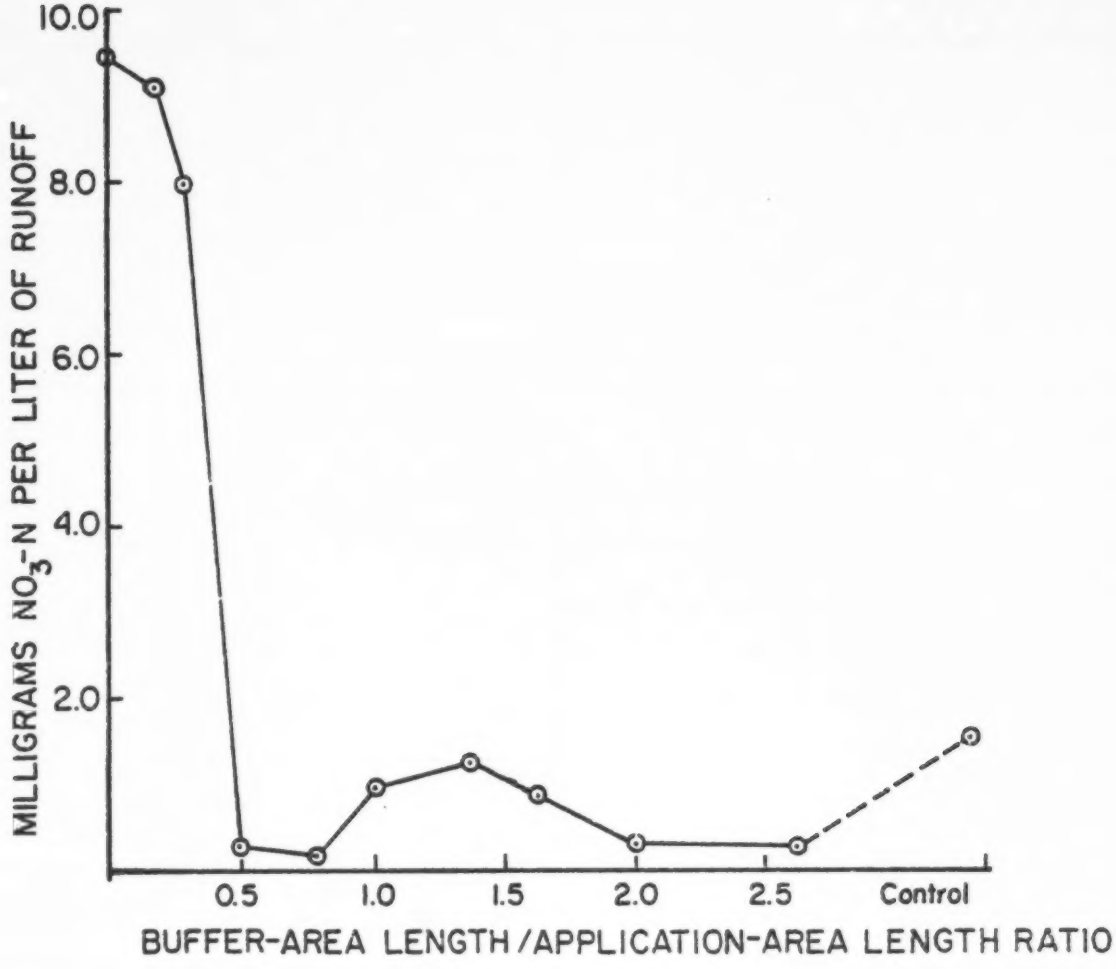


Figure 17. Average NO_3-N concentrations for the various buffer-area length/application-area length ratios.

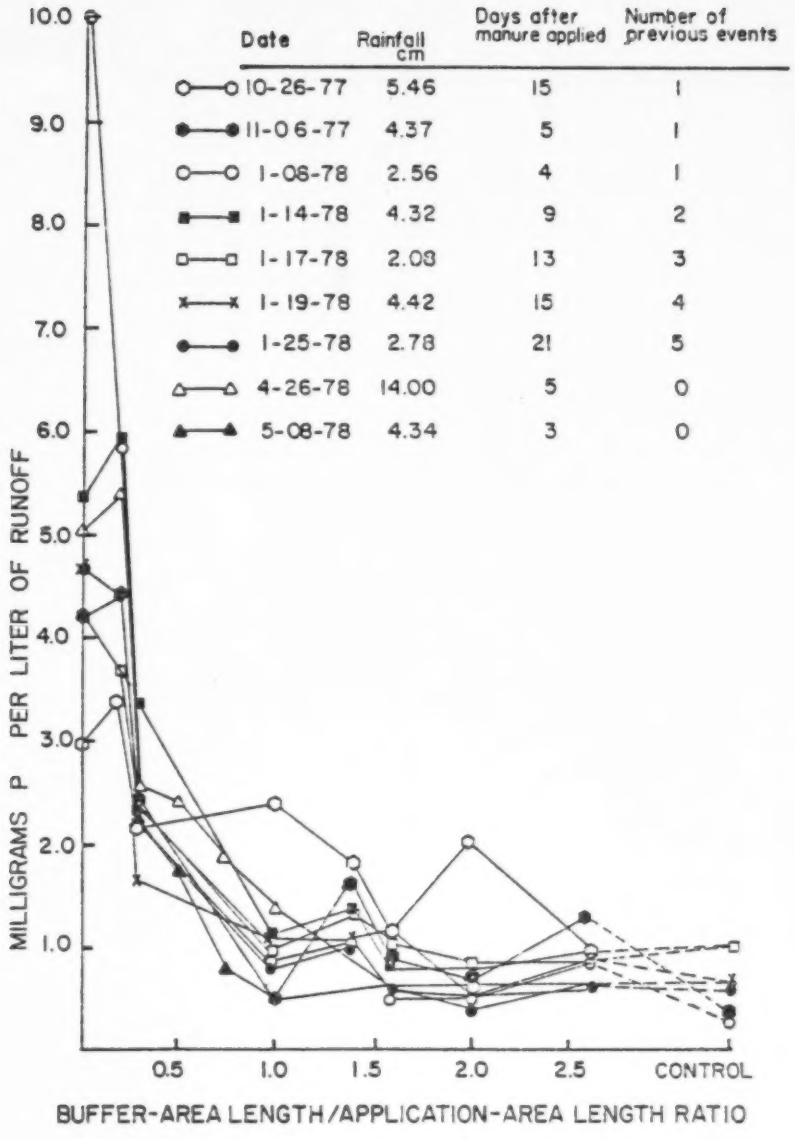


Figure 18. Effectiveness of the grass buffer zone in removing P from rainfall runoff.

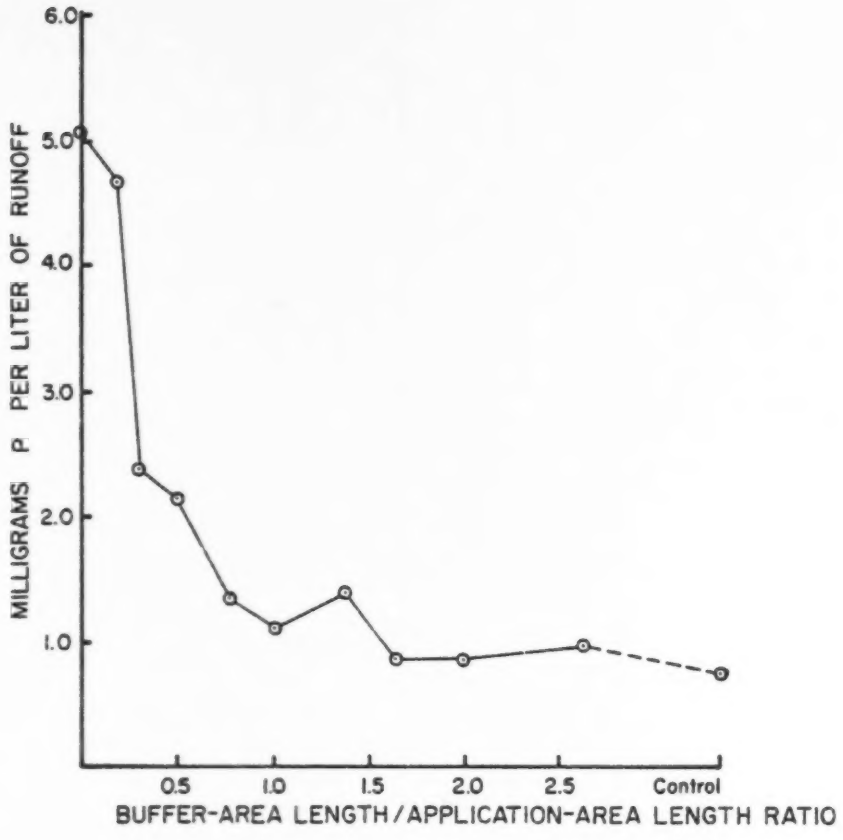


Figure 19. Average P concentrations for the various buffer-area length/application-area length ratios.

TABLE 7. $O\text{-}PO_4\text{-}P/P$ RATIOS FOR FOUR RAINFALL EVENTS

Date	Buffer area/ application area ratio	$O\text{-}PO_4\text{-}P$	P	$O\text{-}PO_4\text{-}P/P$ ratio
		--------mg/ℓ--------		
1-8-78	0.0	11.00	11.25	0.98
	0.2	4.18	4.50	0.93
	0.3	2.78	3.27	0.85
	1.0	0.63	1.20	0.53
	1.4	1.47	1.49	0.99
	1.6	0.71	0.90	0.79
	2.0	0.62	1.13	0.55
	2.6	1.00	1.10	0.91
	CONTROL	0.37	0.83	0.45
1-17-78	0.0	5.03	6.43	0.78
	0.2	3.68	3.98	0.92
	0.3	2.60	2.63	0.99
	1.0	0.38	0.74	0.51
	1.4	1.49	1.95	0.76
	1.6	0.60	0.83	0.72
	2.0	0.33	0.78	0.42
	2.6	0.83	0.83	1.00
	CONTROL	0.69	1.05	0.65

(continued)

TABLE 26 (continued)

Date	Buffer area/ application area ratio	$O\text{-}PO_4\text{-}P$	P	$O\text{-}PO_4\text{-}P/P$ ratio
		----------mg/ℓ---------		
1-19-78	0.0	5.25	5.31	0.99
	0.2	5.33	5.63	0.95
	1.0	0.57	0.75	0.76
	1.4	1.19	1.28	0.93
	1.6	0.56	0.78	0.72
	2.0	0.30	0.60	0.50
	2.6	0.50	0.90	0.56
	CONTROL	0.60	0.75	0.80
4-26-78	0.0	4.95	5.03	0.98
	0.2	5.23	5.40	0.97
	0.3	2.50	2.63	0.95
	0.5	2.51	2.55	0.98
	0.75	1.59	1.85	0.86
	1.0	0.68	1.39	0.49
	1.6	0.53	0.56	0.94
	2.0	0.38	0.53	0.72
	CONTROL	0.53	0.68	0.78

manured areas. Variation in P at lower concentrations could be caused mainly by sediment-associated erosion phenomena.

COD Concentration Reduction Through Buffer Zones

The mg/ℓ of COD in the runoff is plotted against buffer-area length/application-area length ratio in Figure 20. The COD concentrations do not show a smooth trend with increasing buffer-area length/application-area length ratio. The COD concentrations of the control are higher than at the 1.0 ratio five out of nine events. The COD concentration for ratios greater than 1.0 ranges from 40-125 mg/ℓ and for ratios less than 0.5 ranges from 45-100 mg/ℓ. The 0.75 ratio is just as effective at the 1.0 ratio in removing the pollution potential for the event measured. The COD concentration at the 0.5 ratio is greater than at the 0.75 and 1.0 ratios indicating concentration reductions are still possible at this point. COD concentrations in the runoff are not compared with the number of previous rainfall events washing manure constituents or the amount of rainfall because of the variability in the measurements.

TOC Concentration Reduction Through Buffer Zones

The mg/ℓ of TOC in runoff is plotted against the buffer-area length/application-area length ratio in Figure 21. The TOC concentration in the runoff at the 2.6 buffer-area length/application-area length ratio is greater than at the 1.0 ratio six out of nine events indicating possibly increased erosion with longer distance. The TOC concentration ranged from 10-30 mg/ℓ for ratios greater than 1.0 and from 12-50 mg/ℓ for ratios less than 0.5. The TOC concentration of the 0.5 and 0.75 ratios are slightly greater than at the 1.00 ratio for the event measured. The number of days after manure is applied has the greatest effect on runoff concentrations since the rainfall events with the highest TOC concentrations (11-6-77, 1-8-78, 4-26-78, and 5-8-78) occurred the least number of days after a manure application. The number of previous rains washing manure constituents has an effect on the TOC concentration as demonstrated by rainfall events 1-8-78 through 1-25-78.

Cl^- Concentration Reduction Through Buffer Zones

The mg/ℓ of Cl^- in the runoff is plotted against the buffer-area length/application-area length ratio in Figure 22. The data is somewhat variable forcing the conclusions to be very general. The Cl^- concentrations of the control are greater than the Cl^- concentrations at the 1.0 buffer-area length/application-area length ratio five out of nine events. The Cl^- concentrations at the 0.5 and 0.75 ratios are slightly higher than at the 1.0 ratio for the event measured. The Cl^- concentration for all the buffer-area length/application-area length ratios are comparatively constant except for rainfall events 1-8-78 and 4-26-78 which occurred soon after manure applications. For the five events during January, the concentrations seem to be affected by the amount of rainfall and time since manure application. For several events, the Cl^- apparently washed from the grass during previous small rainfall events and did not contribute to the Cl^- concentration during the rainfall events measured.

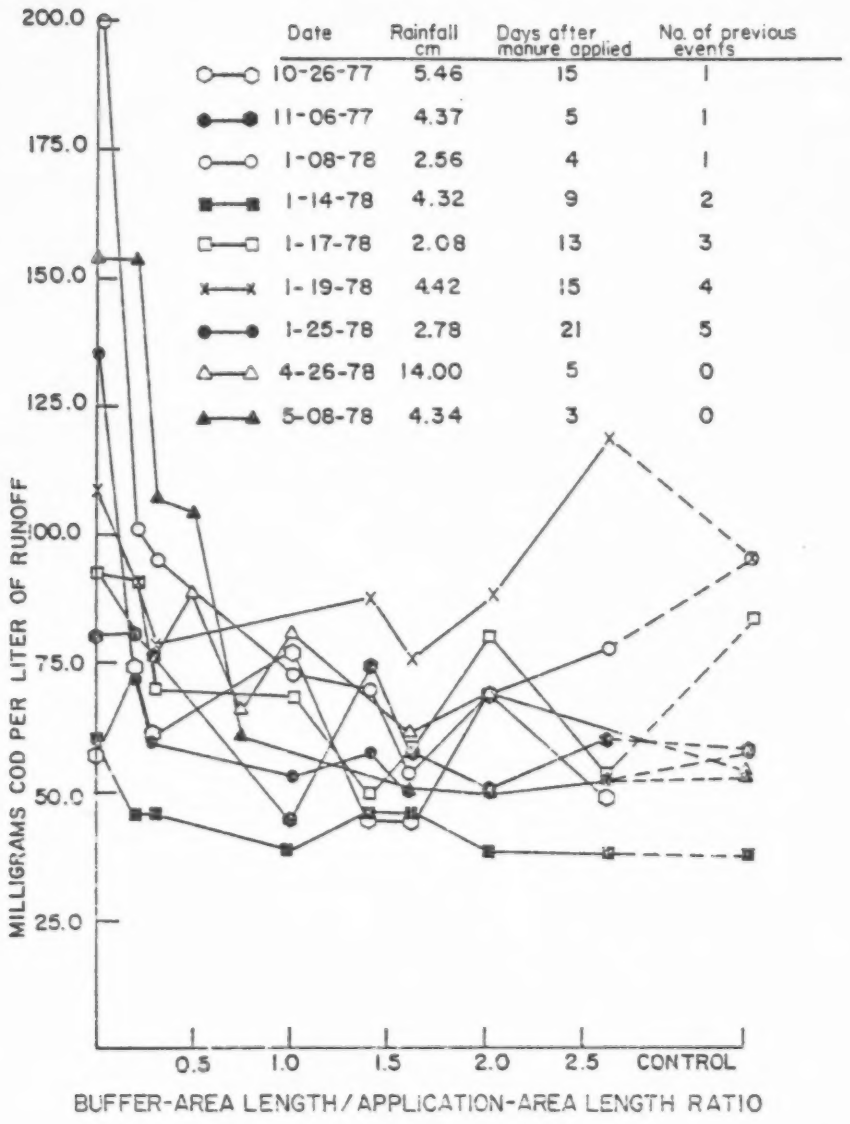


Figure 20. Effectiveness of the grass buffer zone in removing COD from rainfall runoff.

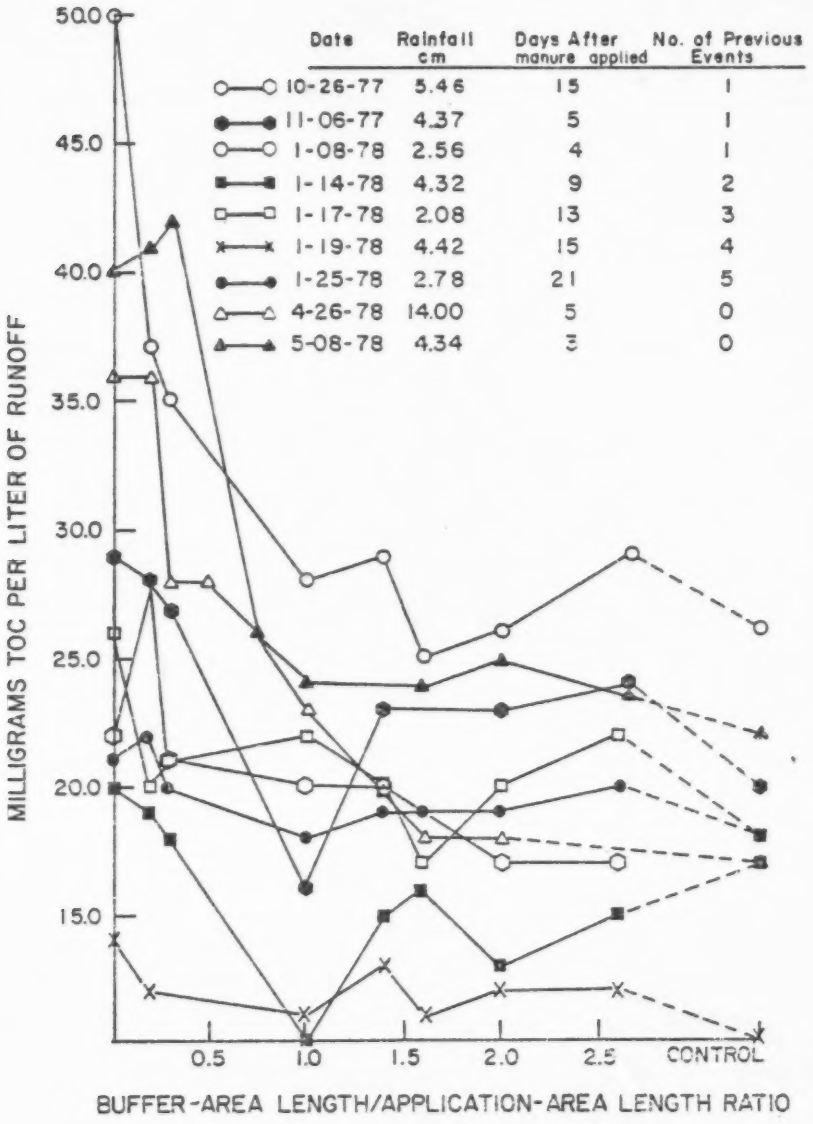


Figure 21. Effectiveness of the grass buffer zone in removing TOC from rainfall runoff.

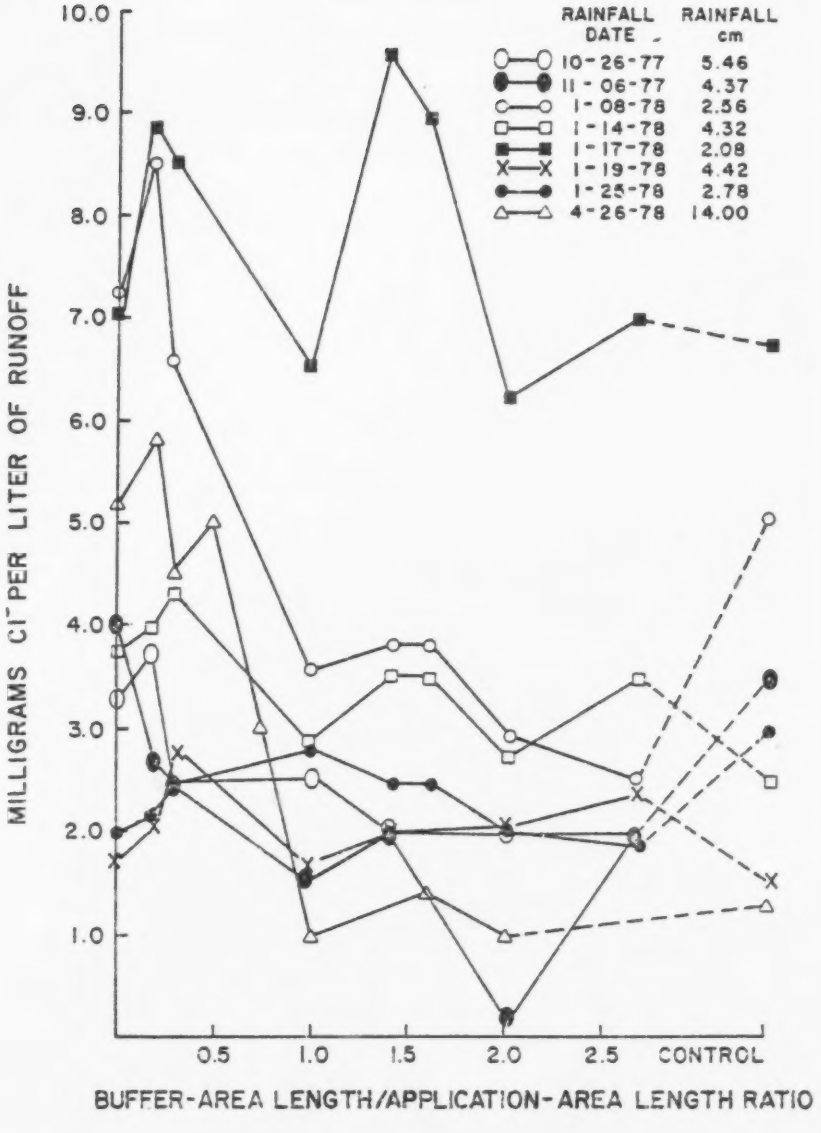


Figure 22. Effectiveness of the grass buffer zone in removing Cl^- from rainfall runoff.

VS/TS Ratio Reduction Through Buffer Zones

The VS/TS ratio is plotted against the buffer-area length/application-area length ratio in Figure 23. The reduction in VS/TS ratio is not a direct measure of the reduction of VS but is a measure of the fraction of solids which are volatile. A large reduction in the ratio usually occurs between the 0 and 1.0 buffer-area length/application-area length ratios. The VS/TS ratio ranges from 0.26 to 0.50 at the edge of the manured area and from 0.14 to 0.25 at the edge of the control area.

The VS/TS ratio of: (1) runoff below the manured area, (2) runoff from the control, (3) the manure, (4) the soil, and (5) the soil-manure complex may be used to obtain estimates of a manure erodability factor (K_{manure}) similar to the soil erodability factor (K_{soil}) used in the Universal Soil Loss Equation. The VS/TS ratio of manure was determined on a number of manure samples obtained from a caged-layer house. The VS/TS ratio of soil was obtained by analyzing the soil from the control plot. Fifty subsamples were composited and mixed to make a soil sample. The VS/TS ratio of a soil-manure mixture was determined by compositing 50 subsamples from the manured area approximately three weeks after a manure application near the end of the field study.

The fraction of the TS in the runoff which are manure may be determined by using equation (20).

$$\left[\frac{VS}{TS}\right]\ \text{Runoff} = \left[\begin{matrix}\text{fraction of the total}\\ \text{solids which are manure}\end{matrix}\right]\left[\frac{VS}{TS}\right]\ \text{Manure} + \left[1-\begin{matrix}\text{fraction of the soil}\\ \text{solids which are manure}\end{matrix}\right]\left[\frac{VS}{TS}\right]\ \text{Soil} \qquad (20)$$

After this value is obtained, equation (20) may be used to determine the fraction of TS which are soil.

$$\begin{matrix}\text{fraction of the TS}\\ \text{which are soil}\end{matrix} = 1 - \begin{matrix}\text{fraction of TS}\\ \text{which are manure}\end{matrix} \qquad (21)$$

Using these two values the following equation may be used to determine the K_{manure}/K_{soil} ratio.

$$\frac{K_{manure}}{K_{soil}} = \frac{\begin{matrix}\text{fraction of the TS}\\ \text{which are manure}\end{matrix}}{\begin{matrix}\text{fraction of the TS}\\ \text{which are soil}\end{matrix}} \qquad (22)$$

Table 27 contains the results of the K_{manure} evaluation when (VS/TS) soil, (VS/TS) manure-area runoff, and (VS/TS) manure are used. These results indicate the K_{manure} value is about the same as the K_{soil} value. Using data presented by Meyer and Ports (1976), the soil erodability factor for the soil at this site is estimated at 0.40; therefore, the K_{manure} value would also be 0.40.

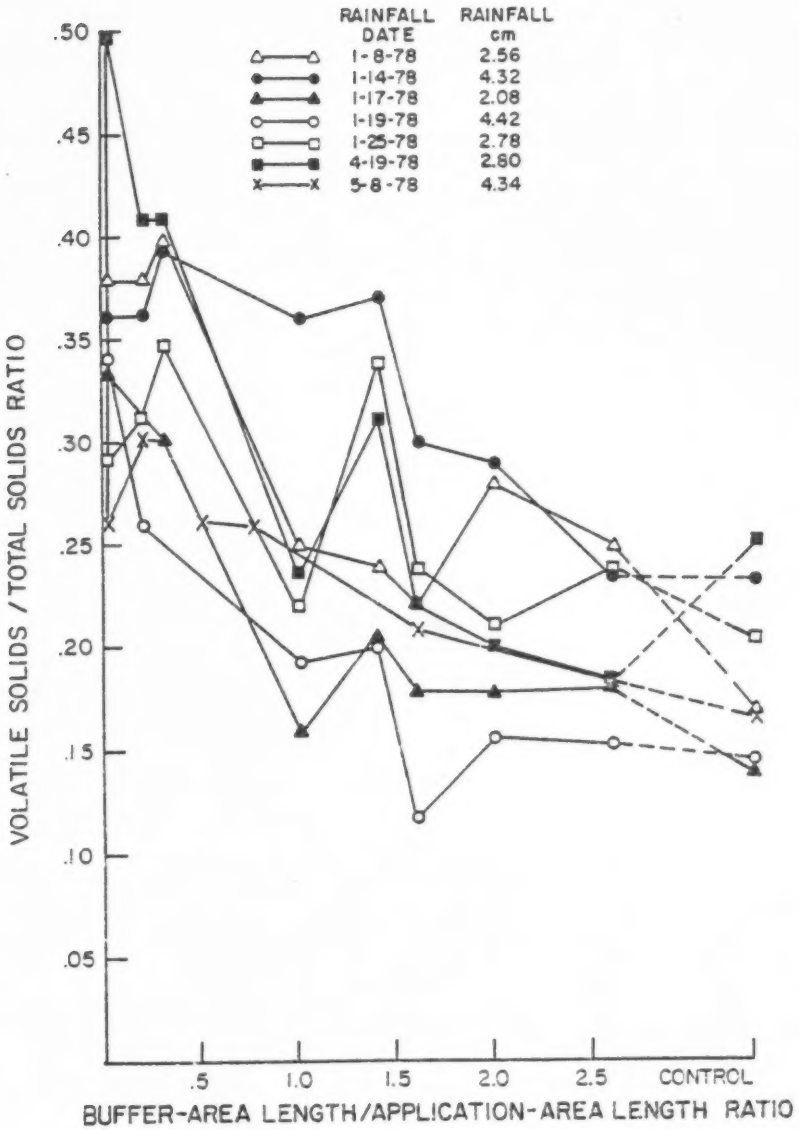


Figure 23. Effectiveness of the grass buffer zone in reducing the VS/TS ratio in rainfall runoff.

TABLE 27. K_{MANURE} EVALUATION USING (VS/TS) MANURED-AREA RUNOFF, (VS/TS) SOIL, AND (VS/TS) MANURE

Rainfall date	1-8-78		1-14-78	
Buffer-area length/ application-area length	0.2	0.0	0.2	0.0
(VS/TS) manured-area runoff	0.379	0.380	0.365	0.361
(VS/TS) soil	0.07	0.07	0.07	0.07
(VS/TS) manure	0.663	0.663	0.663	0.663
Fraction of the total solids which are manure	0.52	0.52	0.50	0.49
Fraction of the total solids which are soil	0.48	0.48	0.50	0.51
K_{manure}/K_{soil}	1.08	1.08	1.00	0.96

Table 28 contains the results of the K_{manure} evaluation for (VS/TS) manured-area runoff, (VS/TS) control runoff (used as soil value), and (VS/TS) manure. By using the (VS/TS) control runoff as the (VS/TS) of the soil, the K_{manure} value is between 0.5 and 0.75 of the K_{soil} value (i.e. K_{manure} is about 0.2 or 0.3 if the soil erodability factor is 0.4).

TABLE 28. K_{MANURE} EVALUATION USING (VS/TS) MANURED-AREA RUNOFF, (VS/TS) CONTROL RUNOFF, AND (VS/TS) MANURE

Rainfall date	1-8-78		1-14-78	
Buffer-area length/ application-area length	0.2	0.0	0.2	0.0
(VS/TS) manured-area runoff	0.379	0.380	0.365	0.361
(VS/TS) control runoff	0.17	0.17	0.23	0.23
(VS/TS) manure	0.663	0.663	0.663	0.663
Fraction of the total solids which are manure	0.42	0.43	0.31	0.30
Fraction of the total solids which are soil	0.58	0.57	0.69	0.70
K_{manure}/K_{soil}	0.72	0.75	0.45	0.43

The results of K_{manure} for (VS/TS) manure-area runoff, (VS/TS) soil-manure, and (VS/TS) manure are shown in Table 29. The K_{manure} value is approximately 0.60 of the soil erodability factor, K_{soil} (i.e. K_{manure} is 0.24 if K_{soil} is 0.40).

TABLE 29. K_{MANURE} EVALUATION USING (VS/TS) MANURED-AREA RUNOFF, (VS/TS) SOIL-MANURE, AND (VS/TS) MANURE

Rainfall date	1-8-78		1-14-78	
Buffer-area length/ application-area length	0.2	0.0	0.2	0.0
(VS/TS) manured-area runoff	0.379	0.380	0.365	0.361
(VS/TS) soil-manure	0.21	0.20	0.21	0.20
(VS/TS) manure	0.663	0.663	0.663	0.663
Fraction of the TS which are manure	0.37	0.39	0.34	0.35
Fractions of the TS which are soil	0.63	0.61	0.66	0.65
K_{manure}/K_{soil}	0.59	0.64	0.52	0.54

The three methods of estimating K_{manure}/K_{soil} gave values from 0.43 to 1.08. This variation could be normal because of differences in surface conditions depending on when manure was applied and how much.

RAINFALL RUNOFF AND POLLUTANT MASS TRANSPORT

The runoff data were inadequate in several events for evaluating effectiveness of grass buffer zones in reducing pollutant mass transport. The tipping bucket samplers used for measuring runoff volumes malfunctioned several times due to friction problems in the pivot mechanism. For the events where runoff data were complete, the runoff amounts varied widely between various plots. Also, the percent of rainfall which became runoff varied from event to event for the same plot. The variation between events for the same plot was probably dependent upon rainfall characteristics, antecedent rainfall, and seasonal variation in vegetation and soil surface infiltration characteristics, while variation from one plot to another for the same event was probably mainly due to variation in soil hydrologic properties caused by land grading operations when the terraces were formed.

Rainfall-runoff data in Table 30 indicate that runoff was usually between 10 and 40 percent of rainfall for large events on Terraces 1, 4, and 7 (buffer-area length/application-area length ratios of 0.3, 0.2, and 0.0, respectively). A range of 10 to 40 percent runoff of total annual rainfall

seems to be common for several land uses (crops and pastures) in humid regions except for extremes in slope or soil infiltration capacity. The variability in runoff for different terraces for the same event was greater than expected because the terraces were thought to be very similar in vegetation and soil hydrologic properties. However, as seen in Table 30, Terraces 4 and 7 were beside each other, had nearly the same amount of manured area, and still differed by a factor of over two (33% compared to 14% runoff) in runoff percent for the average of seven events each. The difference in average pollutant concentration for Terraces 4 and 7 (buffer-area length/application-area length ratios of 0.2 and 0.0, respectively) was less than 20% for all pollutants (Table 24). Thus, if one calculates pollutant mass transport using total runoff and average concentration of all events, the limited data in this study suggests that the variation in amount of runoff between plots or sites has more effect than variation in concentration.

TABLE 30. RUNOFF VOLUMES FOR LARGE RAINFALL EVENTS

Date	Rainfall (cm)	Runoff					
		Terrace 1		Terrace 4		Terrace 7	
		(cm)	(%)	(cm)	(%)	(cm)	(%)
10-26-77	5.46	0.57	10	1.14	3	0.61	11
11-6-77	4.37	1.12	26	1.48	34	0.46	10
1-8-78	2.56	-	-	0.70	27	-	-
1-14-78	4.32	-	-	2.27	53	0.93	22
1-17-78	2.08	-	-	0.75	36	0.24	12
1-19-78	4.42	-	-	2.20	50	1.26	28
1-25-78	2.78	-	-	-	-	0.32	12
4-26-78	14.00	-	-	-	-	-	-
5-8-78	4.34	1.45	33	1.24	29	0.17	4
Average % Runoff			23		33		14

BUFFER LENGTHS BASED ON MODEL AND EXPERIMENTAL RESULTS

A summary of experimental data for P and TKN concentrations in runoff from grass buffer zones is shown in Figure 24. The application-area lengths were 10-13 m (Bingham, 1979) and 24 m (Thompson, 1978). The data suggest that a 100 percent reduction in concentration (subtracting control) is reached between the 0.5 and 1.0 buffer-area length/application-area length

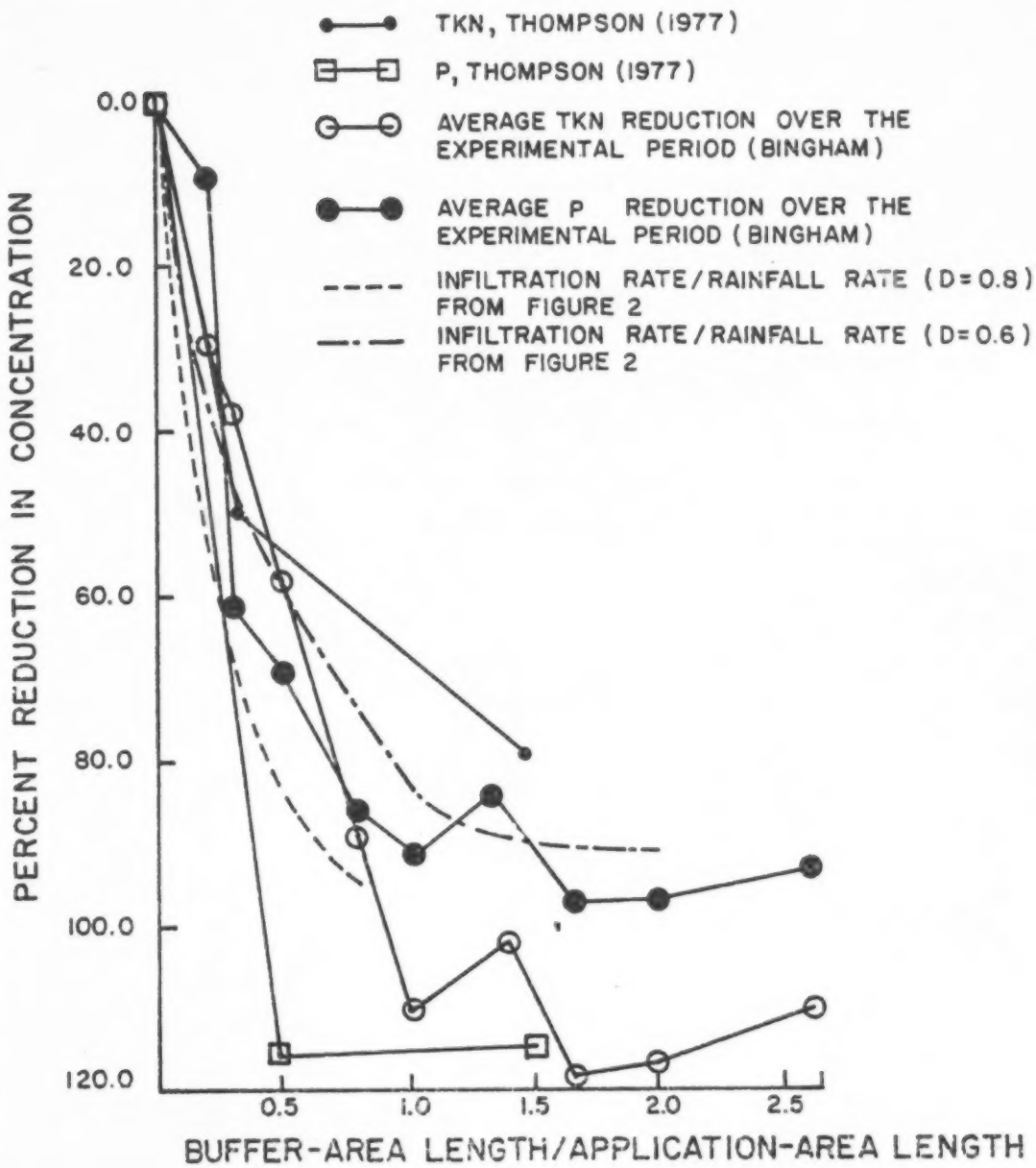


Figure 24. Comparison of experimental and model results.

ratio. As seen in Figure 24, the infiltration-dilution theoretical model would predict similar reductions for a D factor of 0.6 to 0.8. Hence, a D factor of 0.7 may be an appropriate design factor for the majority of the runoff events. Therefore, if the magnitude of the pollution potential is known, the percent reduction needed to improve the water quality to a desired standard can be determined and the appropriate buffer-area length/application-area length ratio can be predicted. While this design is not based on an extreme infiltration and rainfall rate, it has some merit since other factors such as vegetation are indirectly accounted for.

Whenever the infiltration rate/rainfall rate (D) ratio for any particular soil and location can be estimated or measured, the model results may be applied directly to determine appropriate buffer-area length/application-area length ratios to improve the water quality to a desired level. Since the measured D factor for a clay loam soil was about 0.7, an estimated D factor for a sandy loam and sandy soil may be 0.8 and 0.9, respectively, based on the relative infiltration rates.

Since the soil hydrology groups are based on infiltration rates and infiltration is a major factor in estimating the required buffer length, a range of required buffer-area length/application-area length ratios for the A, B, C, and D hydrology groups may be useful. As the amount of clay in a particular hydrology group decreases, the buffer-area length/application-area length ratio would decrease. To reduce concentrations to background levels in the experimental study, a buffer-area length/application-area length ratio of about 1.0 was required for the clay loam soil studied. Since the clay loam soil is probably in the lower part of the C hydrology group, a 1.0 ratio at the lower end of the range may reduce the pollution potential between 90 and 100 percent. No buffer-area length would be required if all the water infiltrated into the soil; therefore, the high infiltrating soils in hydrology group A need only a small buffer-area length/application-area length ratio, probably less than 0.1. An example of a hypothetical range for each group is shown in Table 31. As more information is collected concerning buffer-area length/application-area length ratios for different soil types, the tabulated values should be revised. Also, if the desired water quality of runoff leaving the buffer area is specified, the required percent reduction in concentration (above background) may be less than the 90-100 percent range (depending upon the concentration of runoff entering the buffer zone) and the buffer zone requirement may be less than suggested in Table 31. In other words, less buffer area would be needed if concentrations greater than background conditions were acceptable.

TABLE 31. HYPOTHETICAL RANGE OF BUFFER-AREA LENGTH/APPLICATION-AREA LENGTH RATIOS FOR THE A, B, C, AND D HYDROLOGY GROUPS

Hydrology group	Buffer-area length/application-area length
A	0.00 - 0.33
B	0.33 - 0.66
C	0.66 - 1.00
D	1.00 - 1.20

More research should be conducted for larger land application sites than those used in this study. Application-area lengths in the range of 8.7 m to 13 m were used in this study and caution should be used when considering application of the results of this study to sites with longer application-area lengths, or when the application area and buffer area are not similar to each other in vegetative cover, soil surface conditions, and hydrologic properties.

REFERENCES

Bingham, Samuel C. 1978. Effect of Grass Buffer Zone Length on Runoff of Pollutants from Land Application Areas. M.S. Thesis. North Carolina State University, Raleigh. 137 pp.

Doyle, R. C., G. C. Stanton, and D. C. Wolf. 1977. Effectiveness of Forest and Grass Buffer Strips in Improving the Water Quality of Manure Polluted Runoff. ASAE Paper No. 77-2501. ASAE, St. Joseph, Michigan.

Edwards, W. M., F. W. Chichester, and L. L. Harrold. 1971. Management of Barnlot Runoff to Improve Downstream Water Quality. In: Livestock Waste Management and Pollution Abatement, ASAE, St. Joseph, Michigan, pp. 48-50.

Gilbertson, C.B., F.A. Norstadt, et al. 1979. Animal Waste Utilization on Cropland and Pastureland. A Manual for Evaluating Agronomic and Environmental Effects. EPA-600/2-79-059. U.S. Environmental Protection Agency, Washington, D.C. 134 pp.

Green, W.H. and G.A. Ampt. 1911. Studies on Soil Physics I. The Flow of Air and Water through Soils. J. Agric. Sci. 4:1-24.

Hershfield, D.M. 1961. Rainfall Frequency Atlas of the United States. Technical Paper No. 40, May. Weather Bureau, Washington, D.C.

Khaleel, R., K. R. Reddy, and M.R. Overcash. 1978. Transport of Potential Pollutants in Runoff Water from Land Areas Receiving Animal Wastes: A Review. ASAE Paper No. 78-2058. ASAE, St. Joseph, Michigan.

Kramer, J.A., D. E. Eisenhauer, R. I. Lipper and H. L. Manges. 1974. A Spray-Runoff System with Recirculation for Treating Beef Cattle Feedlot Runoff. ASAE Paper No. MC-74-301. ASAE, St. Joseph, Michigan.

Li, R.M., M. A. Stevens, and D. B. Simons. 1976. Solutions to Green-Ampt Infiltration Equation. Journal of the Irrigation and Drainage Division. ASCE, Vol. 102, No. IR2, June. pp. 239-248.

Loehr, R.C. 1974. Agricultural Waste Management. Academic Press, Inc., New York. 576 pp.

Mein, R. G. and C. L. Larson. 1971. Modeling the Infiltration Component of the Rainfall-Runoff Process. Bulletin 43. Water Resources Research Center, University of Minnesota, Minneapolis.

Musgrave, G. W. 1955. How Much of the Rain Enters the Soil? In: USDA Yearbook of Agriculture, Water. pp. 151-159.

Overcash, M.R., D. M. Covil, J.W. Gilliam, P.W. Westerman, and F. J. Humenik. 1976. Overland Flow Pretreatment of Wastewater. Report No. 117, Water Resources Research Institute, The University of North Carolina, Raleigh. 140 pp.

Meyer, L.D. and M.A. Ports. 1976. Mini-Course 1, Prediction and Control of Urban Erosion and Sedimentation. National Symposium on Urban Hydrology, Hydraulics, and Sediment Control. University of Kentucky, Lexington.

Reddy, K.R., R. Khaleel, M.R. Overcash, and P.W. Westerman. 1979. A Non-Point Source Model for Land Areas Receiving Animal Wastes: I. Mineralization of Organic Nitrogen. Trans. of ASAE 22(4):863-872.

Reddy, K.R., R. Khaleel, M.R. Overcash, and P.W. Westerman. 1978. Phosphorus-A Potential Nonpoint Source Pollution Problem in the Land Areas Receiving Long-Term Application of Wastes. In: Proc. Best Management Practices for Agriculture and Silviculture. Tenth Annual Cornell Conf. Ann Arbor Science, Ann Arbor, Michigan. pp. 193-211.

Ross, B.B., D.N. Contractor, E.A. Li, V. O. Shanholtz and J.C. Carr. 1976. A Model for Predicting Flood Hazards Due to Specific Land-Use Practices. Bulletin 99. Virginia Water Resources Research Center. Virginia Polytechnic Institute and State University, Blacksburg.

Schuman, G.E., M. A. Stanley and D. Knudsen. 1973. Automated Total Nitrogen Analysis of Soil and Plant Residues. Soil Sci. Soc. Am. Proc. 37:480-481.

Sievers, D.M., B.B. Garner, and E. E. Pickett. 1975. A Lagoon-Grass Terrace System to Treat Swine Waste. Proceedings of the Third International Symposium on Livestock Waste, ASAE Publ. PROC-275. ASAE, St. Joseph, Michigan. pp. 541-543, 548.

Soil Conservation Service, USDA. 1964. Section 4, Hydrology. SCS National Engineering Handbook. Chapter 7.

Standard Methods for the Examination of Water and Wastewater. 1971. Thirteenth Edition. American Public Health Assoc., Washington, D.C. 847 pp.

Sutton, A.L., D.D. Jones, and M.C. Brumm. 1976. A Low Cost Settling Basin and Infiltration Channel for Controlling Runoff from an Open Swine Feedlot. ASAE Paper No. 76-4516. ASAE, St. Joseph, Michigan.

Swanson, N.P., C.L. Linderman, and L.N. Mielke. 1975. Direct Land Disposal of Feedlot Runoff. Proceedings of Third International Symposium on Livestock Waste, ASAE Pub. PROC-275. ASAE, St. Joseph, Michigan.

Thompson, Dale B., T.L. Loudon, and J.B. Gerrish. 1979. Animal Manure Movement in Winter Runoff for Different Surface Conditions. In: Best Management Practices for Agriculture and Silviculture. Tenth Annual Cornell Conf., Ann Arbor Science, Ann Arbor, Michigan. pp. 145-157.

Vanderholm, D.H., E. C. Dickey, J.A. Jackobs, R.W. Elmore and S.L. Spahr. 1979. Livestock Feedlot Runoff Control by Vegetative Filters. EPA-600/2-79-143. R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma. 65 pp.

Willrich, T.L. and J. O. Boda. 1976. Overland Flow Treatment of Swine Lagoon Effluent. ASAE Paper No. 76-4515. ASAE, St. Joseph, Michigan.

Young, R. A., T. Huntrods and W. Anderson. 1978. Effectiveness of Non-structural Feedlot Discharge Control Practices. ASAE Paper No. 78-2572. ASAE, St. Joseph, Michigan.

BIBLIOGRAPHY

Asmussen, L.E., A. W. White, Jr., E. W. Hauser, and J.M. Sheridan. 1977. Reduction of 2, 4-D Load in Surface Runoff Down a Grassed Waterway. Journal of Environmental Quality 6(2):159-162.

Broderson, J.M. 1973. Sizing Buffer Strips to Maintain Water Quality. M.S. Thesis. University of Washington, Seattle.

Bulter, R.M., E. A. Myers, J. N. Walter, and J.V. Husted. 1974. Nutrient Reduction in Wastewater by Grass Filtration. ASAE Paper No. 74-4024. ASAE, St. Joseph, Michigan.

Dickey, E.C., D.H. Vanderholm, J.A. Jackobs, and S.L. Spahr. 1977. Vegetative Filter Treatment of Feedlot Runoff. ASAE Paper No. 77-4581. ASAE, St. Joseph, Michigan.

Eisenhauer, D.E., R.I. Lipper and H.L. Manges. 1973. Experience with a Spray-Runoff System for Treating Beef Cattle Feedlot Runoff. ASAE Paper No. MC-73-302. ASAE, St. Joseph, Michigan.

Erman, D.C., J.D. Newbold, and K.B. Roby. 1977. Evaluations of Streamside Bufferstrips for Protecting Aquatic Organisms. Department of Forestry and Conservation. University of California, Berkeley.

Fitzsimmons, D. W., J.R. Busch, R.B. Long, K.H. Linderberg, G.M. McMaster, C.E. Brockway, L.R. Conklin, G.C. Lewis, C.W. Berg, and E. L. Michalson. 1978. Evaluation of Measures for Controlling Sediment and Nutrient Losses from Irrigated Areas. Idaho Agricultural Experiment Station, University of Idaho, Moscow.

Frere, M.H. 1971. Adsorption and Transport of Agricultural Chemicals in Watersheds. ASAE Paper No. 71-0749. ASAE, St. Joseph, Michigan.

Gunther, R. W. and J.K. Mitchell. 1976. The Effects of Manure Application on Runoff, Erosion, and Nutrient Losses. Unpublished M.S. Thesis, Department of Agricultural Engineering, University of Illinois at Urbana-Champaign.

Hayes, J.C. and B.J. Barfield. 1977. Filtration of Non-Homogeneous Sediment by Simulated Vegetation. ASAE Paper No. 77-2513. ASAE, St. Joseph, MI.

Karr, J.R. and I.J. Schlosser. 1977. Impact of Near-Stream Vegetation and Stream Morphology on Water Quality and Stream Biota. EPA-600/3-77-097. University of Illinois at Urbana-Champaign.

Lindley, J.A. 1973. Grass Filtration Beds for Disposal of Milking Center Waste. Univ. of Connecticut Cooperative Extension Service Bulletin WWD. Storrs, Connecticut.

Norman, D.A., W.M. Edwards, and L.B. Owens. 1978. Design Criteria for Grass Filter Areas. ASAE Paper No. 78-2573. ASAE, St. Joseph, Michigan.

Schwab, G.O., R.K. Frevert, T.W. Edminster, and K.K. Barnes. 1966. Soil and Water Conservation Engineering. John Wiley and Sons, Inc., New York.

Skaggs, R.W., L.E. Huggins, E. J. Monke, and G. R. Foster. 1969. Experimental Evaluation of Infiltration Equations. Transactions of ASAE 12 (6):822-828.

Stewart, B.W., D.A. Woolhiser, W.H. Wischmeir, J.H. Caro, and M.H. Frere. 1975. Control of Water Pollution from Cropland. Vol. I & II. EPA 600/2-75-026. U.S. Environmental Protection Agency, Washington, D.C.

Sweeten, J.M. 1975. Premise for Justification of ANCA Distance-to-Stream Factor. ANCA Special Subcommittee on Feedlot Runoff Control. Texas Agricultural Extension Service. Texas A & M University, College Station.

Thomas, R. E. 1974. Feasibility of Overland Flow Treatment of Feedlot Runoff. EPA-660/2-74-062. U.S. Environmental Protection Agency, Washington, D.C. 78 pp.

Thompson, Dale B. 1977. Nutrient Movement During Winter Runoff from Manure Treated Plots. M.S. Thesis. Michigan State University, East Lansing.

Timmons, D.R., R. F. Holt, and J.J. Latterell. 1970. Leaching of Crop Residues as a Source of Nutrients in Surface Runoff Water. Water Resources Research 5(5):1367-1375.

Walter, M.F., T.S. Steenhuis, and D. A. Haith. 1977. Soil and Water Conservation Practices for Pollution Control. ASAE Paper No. 77-2506. ASAE, St. Joseph, Michigan.